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PUBLIC HEALTH RISKS ASSOCIATED WITH THE CANDU NUCLEAR FUEL CYCLE - NON-RADIOLOGICAL RISKS

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ABSTRACT

This report analyzes in a preliminary way the risks to the public posed by the CANDU nuclear fuel cycle. Part 1 considers radiological risks, while part 2 evaluates non-radiological risks. The report concludes that, for radiological risks, maximum individual risks to members of the public are less than 10^{-5} per year for postulated accidents, are less than 1% of regulatory limits for normal operation and that collective doses are small, less than 3 person-sieverts. It is also concluded that radiological risks are much smaller than the non-radiological risks posed by activities of the nuclear fuel cycle.

RÉSUMÉ

Le présent rapport présente une analyse préliminaire des risques que le cycle du combustible nucléaire CANDU comporte pour le public. La Partie 1 traite des risques radiologiques, alors que la Partie 2 examine les risques non radiologiques. Le rapport propose en conclusion que dans le cas des risques radiologiques, les risques maximaux pour une personne du public sont inférieurs à 10^{-5} par année en ce qui a trait aux accidents hypothétiques, inférieurs à 1 pour 100 des limites réglementaires associées à l'exploitation courante, et que les doses collectives sont faibles, c'est-à-dire inférieures à trois personnes-sievert. On y conclue, en outre, que les risques radiologiques sont beaucoup plus faibles que les risques non radiologiques qui résultent des activités liées au cycle du combustible nucléaire.

DISCLAIMER

The opinions expressed in this report are those of the authors and do not necessarily reflect those of the Atomic Energy Control Board.

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INTRODUCTION

Nuclear energy accounts for a signicant fraction of the total energy used in Canada and this fraction should increase in the years ahead. Consequently it was deemed desirable to study the non-radiological hazards associated with the CANDU nuclear fuel cycle and the results obtained are presented in this report. The whole fuel cycle was considered, from the uranium mining to the waste disposal.

The risks were separated according to the source of hazard (mining, milling, fuel fabrication, etc.), the severity of hazard (injury or death) and the origine of hazard (transportation, handling, spontaneous failure, etc.).

In risk assessment the factual data on accidents, their causes, severities and frequencies, were used as much as possible. These data were compiled from the literature, from operators of nuclear facilities and from other sources. In many instances, the factual data on accidents are limited or non-existent. In these cases the physical models were constructed and used in their place. The models used have been compiled from technical reports or scientific journals.

Substantial effort was devoted to the assessment of the accuracy of the models and the data used in risk evaluation. The uncertainty associated with the data was incorporated into calculations of hazard levels and is reflected in results obtained.

All important hazardous substances involved in the CANDU nuclear fuel cycle were considered and the risks resulting from their use were calculated.

This report has been prepared in the hope that it will calculate, apparently for the first time, the non-radiological risks associated with the use of the nuclear fuels and it constitutes only a first step along the road to the better understanding of these difficult problems. The specific risks identified and evaluated in this work should be balanced against the benefits resulting from the use of the nuclear fuels or against the risks inherent in other fuels. I take this opportunity to task the followings individuals we assisted in specified aspects of this study: K. Asmis, R. Hawkins, L. Huong and T. Viglasky.

Although I have received much help from many persons, the responsibility for the opinions expressed and the results obtained is solely mine.

1. METHODOLOGY

Risk assessment is a new and developing science in which safety of different technological processes is assessed and the risk to the workers and the public is calculated. Risk assessment methodology usually consists of the following steps:

1) Hazard identification is the recognition of a hazard, the answer to the question: what constitute a treat? For most of human history, the identification of hazards arose from direct human experience of events and their consequences. To estimate chemical hazards from nuclear fuel cycle, a different approach must be used. Hazard can be identified from consideration of material properties, quantities available and the conditions of the material in process handling or storage. For example, any toxic gas in sufficient quantity constitutes a hazard. A liquid held under pressure at a temperature above its atmospheric boiling tends to flash on release constitutes also a potential hazard. Another category of hazards is constituted by moving objects, the transportation hazard being the major one. Fires and explosions is another obvious example of hazards. Other known hazards such as electrocution, falling objects, fals, etc. do present a danger to workers but not to the public and are not included in our study.

2) Risk estimation is the measurement of threat potential of the hazard, an answer to the question: how often do the danger-creating events occur? It seeks to measure the probability of an event of some stated magnitude. Methods used in risk

estimation are intuition, extrapolation, testing and modelling. Intuition is an ability to make a judgement on the probability of an event based on personal experience and feelings. Extrapolation is the estimation of the likelihood of future events from past experience. When there is little experience availabe, for example when the safety of previously little used chemical must be assessed, it is possible to extrapolate from the experience gained for a chemical with similar properties. Testing is a procedure in which probability of an event, for example pipe failure, is experimentally established by repeated tests. It is usually very expensive and time consuming. Certain events cannot be experimentally tested or the cost would be prohibitive. In such cases modelling can be used. Best known such technique is the "fault tree analysis".

3) Estimation of consequences is the measurement of number of fatalities, injuries and illnesses caused by a certain event, an answer to question: who and how many will be hurt? Assessment of consequences depends on the nature of event. For toxic chemicals, the concentration in the air must be calculated as a function of distance and time. For traffic accidents resulting in a spill, we must postulate the amount released, release rate, weather conditions, wind speed, population density and other factors which may play an important role under special circumstances.

4) Calculation of impact parameters. These are basically products of the probability of an event and its consequences.

5) Social evaluation is the meaning attributed to the measurement of threat potentials. Social evaluation address the ethical questions and is usually left to the society and its representatives to decide.

In this study we will consider only acute hazards due to chemicals used in the nuclear fuel cycle. Knowledge of chronic hazards from chemicals is limited to few substances such as sulfur dioxide and sulfates, and large uncertainty is attached to the mortality parameters which are known. Among acute hazards considered are toxicity, fires and explosions which would cause death. Sublethal acute hazards considered are injuries and illness; only primary effect hazards are included in the study. Secondary effects which are more numerous but much less probable are excluded. By secondary effects we understand such events by which primary chemical agent released during an accident would react with another chemical, and a dangerous product would result. For example, one can envision an accident in which a truck loaded with sulphuric acid would crash into a storage area containing potassium ferrocyanide. Chemical reaction could take place resulting in the production of hydrogen cyanide, a deadly poison. The probability of such event is very low but the consequences could be very serious. Due to the scope of this study, it would be nearly impossible to inventory and assess all such occurrences.

In our report we will use the following notation for different types of hazards:

- H_1 is a hazard due to the presence of a toxic chemical at the site involved in the nuclear fuel cycle. Among release modes which may occur for this type of hazard are burst of storage tanks, handling errors, production upsets, plane crashes and

earthquakes. H_1 is basically time and inventory dependant. It does not depend directly on the amount of fuel produced.

- H_2 is a hazard due to the transportation and toxicity of chemicals. It includes deaths and injuries which would occur as a consequence of a traffic accident resulting in a spill of the chemical. H_2 is directly proportional to the amount of fuel produced.

- H_3 is a hazard due to the physical deaths and injuries during traffic accidents. Poisoning deaths are included in H_2. It is also proportional to the amount of fuel and energy produced.

- (i) is used to indicate injuries. For example, $H_1(i)$ means danger of injury from stationary operations.

1.1 Pathway analysis

A hazardous substance (toxic, corrosive, inflammable or explosive chemicals) is usually isolated from the public by one or more engineered barriers (reactor vessel, wall, piping, storage tank walls, etc.) and a space separation (exclusion area).

Such substance can present a hazard to man only if the engineered barrier(s) is damaged or destroyed either by an internal (corrosion, stress, pressure, etc.) or an external (accident, fire, explosion, earthquake) cause and if the substance can find a pathway to the public. Consequently, a hazard is proportional to the probability of occurence of the initiating cause and the probability of the realization of a certain pathway.

Among the different pathways possible (Figure 1), the atmospheric diffusion of toxic gases is the most important one and is treated in more details later. The aguatic diffusion of toxic liquids constitutes an acute danger for surface waters and a chronic danger for mineral waters. In both cases the presence of these chemicals can be easily detected by taste or by a chemical analysis and the hazards due to the consumption of the poisoned water can be easily avoided. The least hazardous are the solid toxic chemicals which can be released as a result of an accident. These solids can be safely removed after an accident and their potential hazard can be entirely eliminated. Consequently among different pathway which can lead to a hazardous situation, only atmospheric diffusion are considered here.

1.1.1 Atmospheric Diffusion

There are many uncertainties involved when an attempt is made to calculate the air diffusion of a toxic gas. Among possible sources of error are the following factors:

1) amount of gas released and the rate of the release;
2) selection of the air dispersion model and the parameters used;
3) height of the release of the calculation of the buyonance factor;
4) atmospheric conditions which will exist during the release such as wind speed and direction, stability of the atmosphere, rain or degree of cloud cover, etc.
5) physical characteristics of surroundings: rugosity of landscape, presence of buildings, albedo of surface, etc.

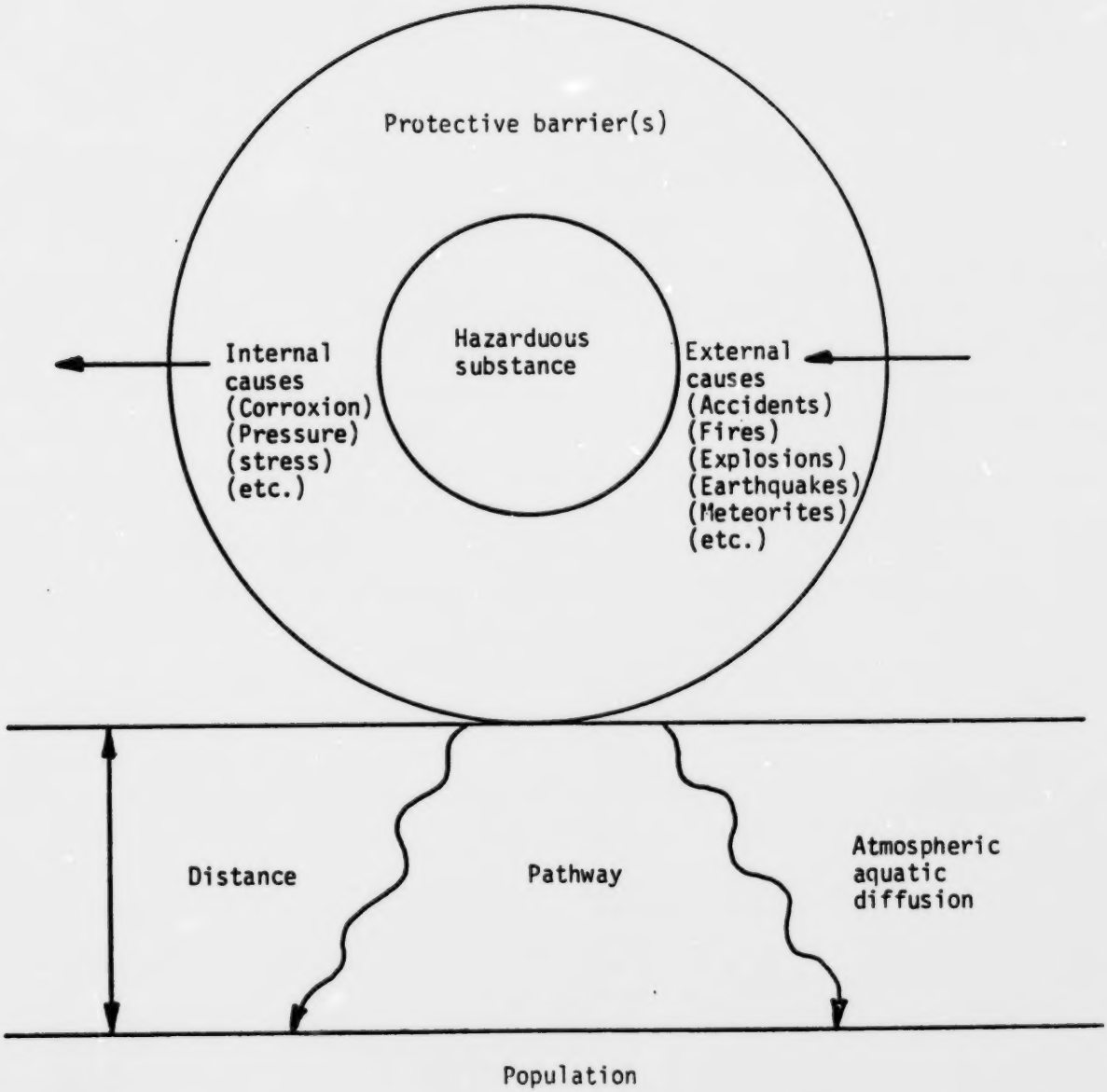

FIGURE 1: Possible pathways of hazardous substances from containment to man

A stream of gas released into the atmosphere will mix with the air under the influence of turbulent eddies and molecular diffusion, a phenomenon globally called "diffusion". The problem of turbulent diffusion in the atmosphere has not yet been uniquely formulated in the sense that a single basic physical model, which can describe all significant features of the proglem, is not available. It was generally accepted that eddy diffusion is many times greater than molecular diffusivity and that, for practical purposes, it can be neglected. By analogy with diffusion from a region of high to low concentration, one can define an eddy diffusivity K so that the flux S is proportional to the gradient of concentration C. Fick's law then gives the equation:

$$S = - K \, \partial C/\partial x \qquad \ldots (1.1)$$

Based on this concept, a general equation may be derived:

$$\frac{\partial C}{\partial t} + u \frac{\partial C}{\partial x} = K_x \frac{\partial^2 C}{\partial x^2} + K_y \frac{\partial^2 C}{\partial y^2} + K_z \frac{\partial^2 C}{\partial z^2} \qquad \ldots (1.2)$$

It is customary to replace the diffusivities K_y, K_z by the standard deviations σ_y, σ_z of the plume concentration in y and z directions. By integrating the differential equation above, we obtain the basic diffusion equation called usually the Gaussian formula*.

$$C(x,y,z,t) = Q \exp \left[-(x-ut)^2/\sigma_x^2/2 - y^2/\sigma_y^2/2\right]$$

$$\left\{\exp \left[-(z- H)^2/\sigma_z^2/2\right] + \exp \left\{-(z+H)^2/\sigma_z^2/2\right\}\right\} \qquad \ldots (1.3)$$

where H = the height of release (m)

u = the wind speed (m/s), considered constant, along x direction

Q = the source intensity (g/s).

---

* Fortran notation.

For a point source, continuous release and at ground level ($z = 0$), we have:

$$C(x,y,H) = Q \exp\left[- y^2/\sigma_y^2/2 - H^2/\sigma_z^2/2\right]/\pi/\sigma_y/\sigma_z/u \quad \ldots (1.4)$$

and the maximum ground level concentration is given by

$$C(x,H) = Q \exp\left(- H^2/\sigma_z^2/2\right)/\pi/u/\sigma_x/\sigma_z \quad \ldots (1.5)$$

The horizontal and vertical standard deviatons σ_y and σ_z can be approximated for different weather types by the following empirical formula cited by Butler([1]):

$$\sigma_y = a\, x^{0.903}, \quad \sigma_z = b\, x^c \quad \ldots (1.6)$$

where x is down-wind distance from the source.

The diffusion parameters were measured by Pasquill([2]) and their fitted constants are presented by Butler([1]).

The Pasquill's diffusion parameters can be built into the Gaussian formula and we obtain:

$$C(x,H) = Q \exp\left[- e\, H^2/x^c\right] x^{-f}/d/u \quad \ldots (1.7)$$

$$\text{where } d = \pi\, ab; \quad e = 9.5\, b^{-2}; \quad f = 0.903 + c/2 \quad \ldots (1.8)$$

The new parameters d, e, f, for different weather conditions are listed in Table 1.

TABLE 1: Fitted Constants for the Pasquill Diffusion Parameters[1]

Class	X_1 (m)	a	b	c	d	e	f	g	h
A	250	0.400	883 E-5	1.51	0.011	6 413	2.41	124 E-6	0.331
B	1 000	0.295	579 E-4	1.09	0.053	149	1.99	613 E-5	0.458
C	1 000	0.200	0.111	0.91	0.070	41	1.81	242 E-4	0.548
D	1 000	0.130	0.392	0.64	0.100	3.25	1.54	0.373	0.786
E	1 000	0.098	0.373	0.59	0.115	3.59	1.49	0.353	0.852
F	1 000	0.073	0.447	0.49	0.102	2.50	1.39	0.569	1.024
Class	X_2 (m)	a	b	c	d	e	f	g	h
A	500	0.400	226 E-6	2.1	284 E-6	979 E-4	3.00	729 E-10	0.238
B	10 000	0.295	579 E-4	1.09	0.054	149	1.99	613 E-5	0.458
C	10 000	0.200	0.111	0.91	0.070	41	1.81	242 E-4	0.549
D	10 000	0.130	0.948	0.54	0.243	0.556	1.44	2.398	0.926
E	10 000	0.098	0.850	0.36	0.877	0.061	1.27	28.44	1.366
F	10 000	0.073	0.066	0.29	0.705	0.053	1.20	38.21	1.689

Frequently we want to calculate the maximum ground level concentration c_{max} and the corresponding downwind distance x_{max}. Expressions for these can be obtained by differenciation of the Gaussian formula and solving it for dC/dx = 0. We will obtain:

$$x_{max} = (f/c/H^2/e) ** (- 1/c) \quad \ldots (1.9)$$

$$C_{max} = Q \exp (- eH^2 x_{max}^{-c}) x_{max}^{-f}/u/d \quad \ldots (1.10)$$

These equations can be further simplified:

$$x_{max} = (g H^{-2}) ** (- h) \quad \ldots (1.11)$$

where g and h are new parameters shown also in Table 1.

Butler's[1] estimates of dispersion coefficients are not the only one used in practice.

Briggs[3] proposed the following formulas for dispersion coefficients which are valid from 100 to 10 000 meter distances from the source

Class	σ_y(m)	σ_z(m)
A	0.22 x F	0.2 x
B	0.16 x F	0.12 x
C	0.11 x F	0.08 x $(1 + 0.0002\ x)^{-0.5}$
D	0.08 x F	0.06 x $(1 + 0.0015\ x)^{-0.5}$
E	0.06 x F	0.03 x $(1 + 0.0003\ x)^{-0.5}$
F	0.04 x F	0.016 x $(1 + 0.0003\ x)^{-0.5}$

where $F = (1 + 0.0001\ x)^{-0.5}$

The proposed CSA Standard N288.2 uses a different set of formulas for σ_z(m) while formulas for σ_y(m) are the same as those above, thus:

$$\sigma_z(x) = g(x)\ F(z_0,x) \qquad \ldots (1.12)$$

where $$g(x) = a_1 x^{b_1}/(1+a_2 x^{b_2}) \qquad \ldots (1.13)$$

$$F(z_0,x) = \ln\{c_1 x\ d_1/[1 + (c_2 x^{d_2})^{-1}]\} \text{ if } z_0 > 10 \text{ cm} \qquad \ldots (1.14)$$

$$F(z_0,x) = \ln\{c_1 x\ d_1/[1 + c_2 x^{d_2}]\} \text{ if } z_0 < 10 \text{ cm} \qquad \ldots (1.15)$$

The parameters a_1, b_1, a_2 and b_2 depend on the atmospheric stability category as shown in Table 2. The parameters c_1, d_1, c_2 and d_2 depend on the meteorological roughness length (z_0) as shown in Table 3. The roughness length, (z_0) is a quantity, which describes the complexity of the land surface in the paths of the plume. (It has units of cm).

TABLE 2: Values for the parameters used in equation 1.13 to calculate vertical standard deviations

Pasquill stability category	a_1	b_1	a_2	b_2
A	0.112	1.060	5.38 E-4	0.815
B	0.130	0.950	6.52 E-4	0.750
C	0.112	0.920	9.05 E-4	0.718
D	0.098	0.889	1.35 E-3	0.688
E	0.0609	0.895	1.96 E-3	0.684
F	0.0638	0.783	1.36 E-3	0.672

TABLE 3: Values for the parameters used in equations 1.14 and 1.15 to calculate vertical standard deviations

Example of surfaces	Roughness length	c_1	d_1	c_2	d_2
- Lawn grass	1 cm	1.56	0.048	6.25 E-4	0.45
- Plowed land	4 cm	2.02	0.027	7.76 E-4	0.37
- Open grassland	10 cm	e	0	0	0
- Tall bushes	40 cm	5.16	-0.098	18.6	-0.225
- Forested area or cities	100 cm	7.37	-0.0957	4.29 E+3	-0.60
- Cities with tall buildgs.	400 cm	11.7	-0.128	4.59 E+4	-0.78

Lets, now compare the dispersion coefficients obtained by these 3 different methods for the distance of 1 km.

TABLE 4: Comparison of dispersion coefficients

Weather class		A	B	C	D	E	F
Butler's	σ_y(m)	205	156	102	67	50	37
Butler's	σ_z(m)	451	108	59	33	22	13
Briggs	σ_y(m)	209	152	104	76	57	38
Briggs	σ_z(m)	200	120	73	38	26	14
CSA, R = 1 cm	σ_y(m)	209	152	104	76	57	38
	σ_z(m)	129	71	49	35	22	11
CSA, R = 400 cm	σ_y(m)	209	152	104	76	57	38
	σ_z(m)	262	143	99	71	45	22

R = Roughness length

As can be seen from the comparison above, estimates of σ_y agree mutually very well but the concordance is not that good for σ_z. Uncertainty in the calculation of concentrations because of this fact is relatively low, became these depend much more strongly on the weather class itself and the height of release.

In conclusion, present formulas for estimating the dispersion coefficients seem satisfactory.

I.1.1.1 Plume Rise

A burning H_2S gas does not immediately move horizontally. In a mild wind, it may undergo a significant rise. This rise of the plume adds to the actual release height Ha; an additional height, ΔH, such that Ha + ΔH is the proper height to use in dispersion calculations.

This height is called effective release height H. Since the height of the release is a very important factor influencing the ground concentration of SO_2, the additional height due to plume rise can be very significant in reducing the danger at the ground level.

A bewildering variety of plume rise formulas were published over the years, mostly for gas escaping from tall stacks.

Brummage([36]) published formulas obtained by multiple regression, which are independent of stack top diameter or gas velocity and which can be used for the burning H_2S gas. These formulas are representative of the great mass of the experimental results but they don't have any theoretical basis.

Class	Weather Conditions	Formula
-	Average	$\Delta H = 0.047\ Q^{0.58}\ u^{-0.70}$
D	Neutral	$\Delta H = 4.8\ Q^{0.26}\ u^{-0.76}$
E	Slightly Stable	$\Delta H = 0.26\ Q^{0.45}\ u^{-0.63}$
F	Fairly Stable	$\Delta H = 0.00027\ Q^{0.92}\ u^{-0.55}$

where Q = heat emission rate in cal/sec
u = mean wind speed in m/sec.

The formulas above are valid for heat fluxes below 10^8 cal/sec.

The heat content of the hot gas is given by:

$$Q = M\ Cp(T-Ta) \qquad \ldots (1.16)$$

where Cp = specific heat of H_2S : 0.24 cal/g/°C
T = gas temperature : 130°C
Ta = ambient air temperature : 25°C.

For the burning gas, we have:

$$Q = M(HC-\Delta T\ Cp) \qquad \ldots (1.17)$$

where HC = the heat of combustion of H_2S
ΔT = the temperature increase.

The second term in the equation above can be neglected and Q becomes:

$$Q = M\ HC \qquad \ldots (1.18)$$

G.A. Briggs is another researcher involved in the development of equations for the plume rise. He shows in his recent work(4) that for hot plume, buoyancy becomes the dominant factor over momentum forces or jet effect, for a distance down-wind an order of 5 seconds times the wind speed. Thus, only buoyant forces need to be considered when dealing with hot H_2S gas escaping from a ruptured line. Intuition indicate that in a light wind, the hot H_2S plume will rise much more than in a strong wind. We expect the ambient temperature gradient to play an important role and also the degree of mixing due to wind instability. All these factors are combined in Briggs' formulas.

Briggs also introduced the buoyant force F which was directly related to the heat content Q of the gas.

$$F = g\ Q/\pi/C/\rho/Ta \qquad \ldots (1.19)$$

By substituting for Q:

$$Q = MC(T-Ta) \qquad \ldots (1.20)$$

we obtain:

$$F = g\, M(T-Ta)/\rho/\pi/Ta \qquad \ldots (1.21)$$

where M = the mass discharge rate (g/s)
g = the gravitational constant : 9.8 ms^{-2}
T = the gas temperature : 408°K
Ta = the ambient air temperature : 303°C
ρ = the density of H_2S : 1539 g/m^3.

Briggs([5]) developed several formulas for the use with F.

Class	Weather Conditions	Formula
E,F	Stable and Windy	$\Delta H = 2.6\ (F/us)^{1/3}$
D	Neutral and Windy	$\Delta H = 1000\ F\ u^{-3}$
F	Stable and Calm	$\Delta H = 5\ F^{1/4}\ s^{-3/8}$

where s is the stability parameter which can be calculated:

$$s = g(G+\Gamma)/T \qquad \ldots (1.22)$$

where G = the abient temperature gradient (typically 0.009°K/m)
Γ = defined as a positive number equal to the adiabatic lapse rate.

Dormuth et Lyon([6]) use for Γ the following values:

Stability class	A	B	C	D	E	F
Lapse rate Γ(°C/100 m)	<-1.9	-1.8	-1.6	-1.0	+0.5	>1.5

For unstable and windy conditions (classes A,B,C), Briggs has proposed another set of formulas.

$$\Delta H = 114\ F^{1/3}\ u^{-1} \qquad x \leq 600 \qquad \ldots (1.24)$$

$$\Delta H = 21\ F^{0.75}\ u^{-1} \qquad x > 600 \qquad F \leq 55\ m^4 s^{-3} \qquad \ldots (1.25)$$

$$\Delta H = 39\ F^{0.6}\ u^{-1} \qquad x > 600 \qquad F > 55\ m^4 s^{-3} \qquad \ldots (1.26)$$

where x is the distance down-wind. Other plume rise formulas can be found in the literature and in some cases may be more useful than Briggs' and Brummage's equations. Perkins([7]) states a formula for unstable or neutral conditions (classes B, C, D).

$$\Delta H = 150\ F\ u^{-3} \qquad \ldots (1.27)$$

which is similar to Briggs' formula for neutral and windy conditions, but gives lower plume rises. Lucas et al.([5]) published a formula for "average" conditions.

$$\Delta H = 24\ Q^{0.25}\ u^{-1} \qquad \ldots (1.28)$$

All these plume rise formula give very different results when applied to the same situation and the lowest plume rise should be used for the calculations. Due to imperfect knowledge of "true" plume rise under different atmospheric conditions, a large degree of uncertainty is injected into results of atmospheric dispersion.

As can be seen from observation of data in Table 5, ratio of the highest and the lowest concentration as calculated from the lowest and the highest plume rise, varies enormously as function of the distance. For this reasoin it is difficult to estimate the accuracy of concentrations of hot or burning gases and uncertainty of results obtained when there is a plume rise, can be only characterized as "unknown".

TABLE 5: Comparison of plume rise results obtained by the different formula

Conditions	B		C		D		E	
Discharge rate (kg/s)	10	1000	10	1000	10	1000	10	1000
Heat input M (cal/s)	36	3600	36	3600	36	3600	36	36000
Buoyancy factor (4-3 ms)	1368	136800	1368	136800	1368	136800	1368	136800
Wind speed (m/s)	4	4	6	6	8	8	4	4
ΔH Brummage (m)					91	301	272	2167
ΔH Briggs (m)	742	1200	494	7844	371	5883	229	1063
ΔH Lucas (m)					232	734		
ΔH Perkins (m)			950	na	400	na	na	na
RHLC at 1 km	na	na	1 E+29	na	na	na	4 E+9	na
RHLC at 10 km	na	na	8	na	15	na	13.7	na
RHLC at 100 km	na	na	1	na	1.3	68	1.4	5 E+23

na = not applicable
RHLC = ratio of the highest and the lowest concentration.

Dimensional analysis of plume rise formulas shows, that Brummage's, Lucas' and Briggs' formulas for unstable conditions dont have dimension in meters which seems to indicate a fundamental weakness of these formulas. The Briggs' formulas for unstable conditions are independent of weather classes which seems strange because what it says in effect is that the plume rise will be the same in very unstable conditions (A) as in midly unstable conditions (C).

That appears to be an unlikely event. In very unstable conditions the plume is mixed more rapidly with the air and should loose its buoyancy sooner than in midly unstable conditions. The final plume rise should be smaller for A class than for C class. More research into this effect appears desirable. A computer modeling of the basic equations may be one approach possible.

1.2 Types of risk

All hazardous substances used by man are handled in a way which should minimize the possibility of their escape and creation of a hazardous situation. Unfortunately, there are many different causes which can damage or destroy barriers retaining the hazardous substances. The different types of risk which may occur will be analyzed in the following section.

1.2.1 Transportation Risk

In order to estimate the danger to the public due to the transportation of materials used in the nuclear fuel cycle, we will consider two basic types of accidents.

1) Direct consequences of traffic accidents involving trucks, rail car, barges or any other vehicles used to transport materials to and from uranium mines, refineries, etc. Among the consequences of accidents, we will be concerned mainly with deaths and injuries inflicted upon the public (pedestrians and bicyclists). Hazards to the professional drivers are excluded from our study.

2) Hazards due to the transportation of toxic chemicals. In this case and accident may not cause any physical injuries to the public but a leak may occur because of the accident and the public may be hurt by the release of toxic chemicals transported.

The first task was to compile the general data on traffic accidents and accident rates.

Probability of an Event per km	P	Reference
1) Canadian Experience		
• Car accidents, 1976	3.6 E-6	8
• Deaths in a car accident, 1976	3.0 E-8	8
• Injury in a car accident, 1976	1.1 E-6	8
• Pedestrian killed by a car, 1976	4.9 E-9	8
• Bicyclist killed by a car, 1976	8.7 E-10	8
• Derailment of a freight car resulting in spill, 1978	2.6 E-8	8
2) British Experience		
• Accident to a petroleum tanker resulting in a spill	1.6 E-8	9
• Accident to a chlorine rail tank resulting in a spill	2.4 E-8	10
• Car accidents involving injuries	1.3 E-6	11
• Car accidents involving fatalities	3.3 E-8	
3) Other Countries		
• U.S., railroad accident rate	9.0 E-6	12
• U.S., trucks accident rate	2.5 E-6	
• Germany, car accidents involving injuries	1.4 E-6	11
• Germany, car accidents involving fatalities	6.2 E-8	11
• U.S., car accidents involving injuries	0.7 E-6	11
• U.S., car accidents involving fatalities	2.9 E-8	11
• Finland, train derailment	1.0 E-7	13

Statistics for deaths and injuries caused by trucks are difficult to obtain and consequently, we will use the average values for all types of vehicles.

One difficulty which is encountered when assessing transportation hazard to the public is to separate deaths and injuries inflicted to the public from those inflicted to drivers and occupants. One approach which can be used is to assume that accident rate for pedestrians killed represent the fraction of the "public" transportation hazard in the overall rate. Using Canadian figures, we can say that hazard to the public amount to 16% of the overall accident rate, and for fatalities and injuries, we will use two basic number:

- Probability of injury due to the transport by road : 1.8 ± 0.1 E-7/km

- Probability of death due to the transport by road : 4.9 ± 0.4 E-9/km.

Risks due to the railway transportation can be calculated from Canadian statistics on this subject([8]). From 1974 to 1978 there were on the average 84 ± 9 and 230 ± 99 persons killed or injured in accidents at highway crossings, while 136 ± 7 E+6 train-km, 109 ± 5 E+6 freight train-km and 7.28 ± 0.3 E+9 freight car-km were travelled. From these we can calculate the average length of a freight train: 67 ± 3 cars - and probabilities of being killed or injured by a train in accident at highway crossing:

- Probability of injury due to the transport by rail : 2.5 ± 1.0 E-8/km

- Probability of death due to the transport by rail : 9.2 ± 1.0 E-9/km.

Another value which is needed when we try to estimate the transportation risks is the probability that the traffic accident involving hazardous materials will result in explosion or release. We hape found in literature 3 such values: Hornyik([12]) from U.S. experience cited values of 0.02 to 0.05; Burschmann([10]) from England has found value of 0.022; and Lautkaski and Mankamo([13]), finish researchers, have published value of 0.017 events/accident. These values are surprisingly close to each other and in this study, we decided to use the value of 0.02.

In our study some fatalities are counted twice. A pedestrian may be killed by a truck transporting hydrogen sulphide to the heavy water plant. During the same accident, a leak may develop and the same person would be poisoned by the gas. It is difficult to take such "double" deaths into account, no such attempt was made. It means only that fatality figures may somewhat over estimate the hazard.

Transportation hazards will be calculated by using two equations. For hazards H_2 due to the toxicity, we have:

$$H_2 = PDP_d \sum A_i W_i \qquad \ldots (1.29)$$

where P = the probability of an accident

D = the distance travelled

P_d = the average population density (25 persons/km^2)

W_i = the probability of occurrence of certain weather conditions

A_i = the affected area under these conditions.

For hazard H_3, we will use:

$$H_3 = PDN \qquad \ldots (1.30)$$

where N = the number of shipments per year
P = the probability of injury (1.8 E-7/km) or death (4.9 E-9/km).

For specific hazard H_3^j, we will apply the following formula:

$$H_3^j = PDQ/S \qquad \ldots (1.31)$$

where Q = quantity of reagent used in order to produce 1 kg of nuclear fuel
S = the unit shipment size in kg.

There are some studies([14]) in which the transportation hazard is expressed by using so called impact parameters which give the average number of fatalities per accident in urban and rural environments. Knowing the relative exposures in these environments, we can calculate H_2 by the following formula:

$$H_2 = PDN\ (E_u M_u + E_r M_r) \qquad \ldots (1.32)$$

where E_u, E_r = relatives exposures to urban and rural environments
M_u, M_r = expected mortalities in these environments.

1.2.2 Seismic Risk

To estimate the seismic risk in a given seismic zone, the statistics will be formulated in a simple form. Consider the series of events in time with magnitude $M > M_0$, and let α be the average number of such events per unit time; then the time series of events can be represented by a Poisson distribution

$$f(n,\Delta t) = \frac{(\alpha\Delta t)^n}{n!} e^{-\alpha\Delta t} \quad \ldots (1.33)$$

$f(n,\Delta t)$ is the frequency of a set of n events in the internal Δt (or the probability of having n events of magnitude $M > M_0$ in Δt). The distribution of the magnitude is given by:

$$N_{ki} = \int_M \alpha e^{-\gamma M} dM \quad \ldots (1.34)$$

N_{ki} is the annual average number of the events of magnitude in the range M_k per unit area. For the number of events of magnitude M in the interval (0,x) is obtained:

$$N = \int_0^x \gamma\alpha e^{-\gamma M} dM = \alpha[1-e^{-\gamma x}] \quad \ldots (1.35)$$

where α and γ are parametric values.

Before proceeding, the following hypotheses may be recapitulated: (a) the number of earthquakes per annum is a random variable of Poisson type with average α (see Eq. (1.33) with Δt = 1 year); (b) the magnitude is a random variable given by Eq. (1.34).

The cumulative distribution of the magnitude is therefore (remember that $\lim_{x \to \infty} N = \alpha$ is the total number of events):

$$F(x) = P[0 < M < x] = 1-e^{-\gamma x} \qquad \ldots (1.36)$$

and therefore the average annual number of events with magnitude $M > x$ is:

$$N_x = \alpha P[M > x] = \alpha e^{-\gamma x} \qquad \ldots (1.37)$$

In order to estimate the probability of a major earthquake which would almost totally destroy a plant and cause quasi-instantaneous release of chemicals (H_2S, NH_3, etc.), the following assumptions were made.

1) The plant is located in Eastern Canada and the values cited by Basham et al.([15]) can be used for parameters α and γ.

2) The plant is situated the "Background" seismic zone as described by Basham et al.([15]).

Consequently the number N of occurences of an earthquake of a magnitude $M > 5$ is equal to:

$$N(> M) = 3\ E\text{-}4\ \exp(-1.84\ (M-5)) \qquad \ldots (1.38)$$

The question of the maximum possible magnitude for an intraplate earthquake (the only one which is applicable to the Eastern Canada) was widely debated, without a satisfactory resolution. Usually the distributions of the probability of an earthquake vs magnitude are

simply extrapolated in linear fashion to the low probability region of the curve. The theoretical basis for this extrapolation is rather weak but it is the only method available for estimating seismic risk for a high magnitude earthquake. This is what was done with equation (1.38) and the following values were obtained.

Magnitude	5	6	7
Probability (events/year)	3 E-4	5 E-5	8 E-6

It is very risky to extrapolate the equation (1.38) for higher magnitudes than 7 and this was not attempted. We simply dont have any reliable data for high magnitude earthquakes occuring in the Eastern Canada.

Precise prediction of the size or location of major earthquakes is not presently possible and the probabilities calculated above indicate rather an order of magnitude than exact values. The parameters used for the calculation of probabilities of earthquakes are not known with high accuracy and results are therefore uncertain. A major long term research program would be needed to improve our predictive capability of earthquakes. Also each site is different and different empirical parameters apply.

1.2.3 Plane Crashes

The possibility of a heavy airplane crashing on a facility involved in nuclear fuel cycle needs to be considered in a study such as this. There are some published data([16]) on this subject, mostly for nuclear power plants([17]) but very little data is available for mines, refineries and heavy water plants. Within the scope of the present work, it was not intended to establish the detailed analysis of flight

TABLE 6: The modified Mercalli intensity scale

	Modified Mercalli Intensity	Ground Acceleration
II	Felt by a few persons at rest, especially on upper floors; suspended objects may swing.	
III	Felt noticeably indoors, but not always recognized as a quake; standing autos rock slightly.	0.005 g
IV	Felt indoors by many, outdoors by a few; at night some awaken; dishes, windows, doors disturbed.	0.01 g
V	Felt by most people; some breakage of dishes, windows, and plaster; tall objects disturbed.	
VI	Felt by all; many frightened and run outdoors; falling plaster and chimneys; damage small.	0.05 g
VII	Everybody runs outdoors; damage to buildings varies depending on quality of construction.	0.1 g
VIII	Panel walls thrown out of frames; fall of walls, monuments; sand and mud ejected; drivers disturbed.	
IX	Buildings shifted off foundations, cracked, out of plumb; ground cracked, underground pipes broken.	0.5 g
X	Most masonry and frame structures destroyed; ground cracked; rails bent; landslides.	1 g
XI	New structures standing; bridges destroyed; fissures in ground; pipes broken; landslides.	
XII	Damage total; waves seen in ground surfaces; lines of sight distorted; objects thrown into air.	5 g

TABLE 7: Postulated relationship between an earthquake magnitude and its effects

Earthquake		Effect on Nuclear Installations
Magnitude (Richter Scale)	Intensity (Mercalli Scale)	
6	VII-VIII	Very little damage and practically no release of chemicals.
7	IX	Small leaks may occur; staff may be endangered but public is safe.
8	X-XI	Major leaks occur; significant release of chemicals; complete inventory may be released over a period of few hours, pipes broken.
9	XII	Nearly total destruction; quasi-instantaneous release of chemicals stored in the pressurized vessels; fast release of chemicals stored in non-presssurized vessels.

patterns around each facility in which an observer on the ground would tally over an extended period of time, the exact numbers and types of airplanes using each particular corridor. Therefore we have used a simple model based on the average flight density. Godbout and Brais([16]) studied statistics and accident rates in Canada (Table 8) and in other countries (Table 9).

From these tables, it can be seen that there were 1,062,091 heavy airplane movements per year and the probability of the on-route crash is, when using U.S. average, 1.3 E-9 events/km. In our analysis, we have excluded crashes on take-off and landing assuming that there is no airport near facility.

According to Statistics Canada([18]) during January to August 1980, 18,560,494 passanger kilometers were flown and the total number of passangers was 16,585 which means that the average flight length is 1,119 km. Using these numbers, the probability P that heavy aircraft will crash on a facility of area A km^2 is equal to:

$$P = ANLR/I_a \qquad \ldots (1.39)$$

where N = the number of flights (1,062,091)
L = the average length (1,119 km)
R = the on-route accident rate (1.3 E-9)
I_a = the densely inhabited area of Canada (10^6 km^2)

$$P = 1{,}062{,}091 * 1{,}119 * 1.3\ E\text{-}9 * A/1E{+}6 \qquad \ldots (1.40)$$

or $$P = 1.5\ E\text{-}6\ A\ (km^2) \qquad \ldots (1.41)$$

Now we can calculate the probability of airplane crash on different facilities.

TABLE 8: Statistics and accident rates for heavy aircraft calculated over the 5-year period 1969-1973 in Canada

Type of airport	Mot or DND airport	Non-mot or DND airport
# of Accidents:		
- Landing	17	26
- Take-off	2	10
# of Movements:		
- Heavy	1,936,681	312,751
- Light	10,302,883	2,611,931
Crash rates (crash/movement):		
- Landing	8.78 E-6	8.31 E-5
- Take-off	1.03 E-6	3.20 E-5

TABLE 9: Calculated heavy aircraft accident rates for countries other than Canada (with the percent of uncertainty in brackets) for the years 1969, 1970, 1971, 1973

Phase of operation	On-route (km^{-1})	Take-off ($movement^{-1}$)	Landing ($movement^{-1}$)
World Average	5.92 E-9 (12.1%)	2.12 E-6 (11%)	4.79 E-6 (7.3%)
United States	1.30 E-9 (30%)	1.00 E-6 (22%)	1.47 E-6 (18%)
United Kingdom	1.49 E-8 (58%)	4.38 E-6 (33%)	8.28 E-6 (24%)
France	3.10 E-8 (50%)	2.29 E-6 (71%)	8.0 E-6 (38%)
Germany	2.00 E-8 (100%)	1.02 E-5 (40%)	1.70 E-6 (100%)

TABLE 10: Probability of a heavy airplane crash on facilities involved in the nuclear fuel cycle

Facility	Surface Area (km^2)	Probability of Crash (events/year)
Heavy water plant	1.0	1.5 E-6
Uranium refinery	0.1	1.5 E-7
Uranium mill	0.1	1.5 E-7
Waste treatment (guess)	0.1	1.5 E-7

Note: Surface areas were estimated from plans.

1.3 Properties of Relevant Chemicals

When assessing consequences of release of toxic chemicals, it is necessary to know their basic physical, chemical and physiological properties. Among important physical properties are boiling point, heat of evaporation, vapor tension as a function of temperature, vapor or gaseous density and heat of combustion. Chemical properties of interest are corrosion potential vis à vis metals, affinity to water and oxygen and association constants in gas phase. Physiological properties relevant to safety studies are the average lethal concentration and exposure, and also the concentration and exposure at which the chemical would cause a specific illness or injury.

1.3.1 Properties of Anhydrous Ammonia

Ammonia is a colorless gas at atmospheric temperature and has a pungent, penetrating odor. This is fortunate, as the gas is both toxic and explosive. There is no cumulative toxic effect as for poison gases in general, but there is a severe burning effect on tissue.

Breathing air containing as little as 5,000 ppm by volume of ammonia normally causes death by suffocation in a short time. Even 2,000 ppm will burn and blister the skin in a few seconds and may produce serious lung oedema. Concentrations above 700 ppm cause eye injury that can cause loss of sight unless treated immediately. The strong odor, however, makes the gas detectable at as low as 20 ppm.

Physiological effects of ammonia on men were compiled by the Matheson Gas Products Ltee([19]) and are listed in Table 11.

TABLE 11: Physiological effects of ammonia on men

Concentration		Effects
(ppm)	(mg/m^3)	
20	12	First perceptible odor
100	60	Irritation of eyes and nasal passages
500	298	Severe irritation of throat, nasal passages and eyes
700	417	Eye injuries
1700	1013	Serious coughing, bronchial spasm, less than 30 min. exposure may be fatal
2000	1192	Skin burns in few seconds
5000	2980	Serious oedema, strangulation, asphyxia; fatal almost immediately

Note: 1 mg/m^3 = 1,677 ppm

From: MATHESON GAS PRODUCTS, Matheson Gas Data Book, 5th ed., 1971.

and SLACK A.V., G.R. JAMES, "Ammonia", Part I, Marcel Dekker Inc., N.Y., 1973.

The threshold limit value for ammonia in work room air adopted by the American Conference of Governmental Industrial Hygienists and by U.S. Congress([20]) is 50 ppm or 35 µg/ℓ. Ammonia is classified as moderately harmful flammable chemical, extremely irritating on a short time exposure and causing skin irritation or burn.

There are very few air quality standards for ammonia. In Ontario, the air quality criterium averaged for 30 min. is 3.6 mg/m^3 ([21]) and in U.S., the Threshold Limit Value for work-room air is 35 mg/m^3 ([20]).

1.3.2 Properties of Hydrogen Fluoride

Hydrogen fluoride is a highly volatile liquid of boiling point 19°C which is stored and handled as a liquefied gas. Its vapor is highly irritant and toxic. The physiological effects of HF on man are listed in Table 12. As can be seen from this table, HF in high concentrations is a dangerous substance. Hydrogen fluoride is chemically very reactive and will attack readily the tissues. It does combine also with humidity and forms hydrofluoric acid which may infiltrate the water supply.

Effects of fluorides on human health were extensively studied over the years. According to Waldbott([22]), fluoride has a strong affinity for magnesium, manganese and other metals which causes it to interfere with the activity of many enzymes and can affect adversely the function of endocrine process.

Most thoroughly documented is an increase in the function of the parathyroid glands, which regulate the metabolism of calcium. Damage to the pituitary gland, the main regulator of water balance in

TABLE 12: Physiological effects of hydrogen fluoride on men

Concentration (mg/m^3)	Effects
0.1	First perceptible odor.
2.5	8 hour daily exposures ACGIH threshold limit value.
25	Exposure for several minutes results in conjunctival and respiratory discomfort. No deaths after 41 hours.
> 50	Severe irritation, paroxysms of coughing, copious discharge from eyes and nose.
>100	No fatality after 5 hour exposure, but severe irritation.
500	Not fatal in 15 minutes, but animals severely affected.
1,000	Not fatal in 30 minutes, but tissue damages.
1,500	Fatal in 5 minutes.

Note: 1 mg/m^3 = 1.3 ppm.

From: NATIONAL ACADEMY OF SCIENCES, Fluorides, 1971, F.A. Patry (ed.), Industrial Hygiene and Toxicology, 2nd Edition, Vol. II, Interscience, 1963.

the human organism, indicated by the occurrence of polydipsia and polyuria (excess thirst and urination), is an early sign of fluoride intoxication. The effect of fluoride on the thyroid gland is not clearly established, although a large volume of research on this subject exists. In large doses, fluoride interferes with the secretion of gastric juice in experimental animals. Experimental and clinical data point to fluoride's adverse effect on kidneys following long-term fluoride intake in minute doses.

The two conspicuous and most thoroughly studied manifestations on which physicians usually depend for the diagnosis of chronic fluoride poisoning are dental and skeletal fluorisis. Dental fluorisis is a permanent defect of tooth enamel, characterized by white chalky patches. In skeletal fluorosis, tissue and ligaments about the joints, especially in the pelvic area and spine, become calcified.

Air quality standards for HF and fluorides have been developed by many government agencies and are resumed in Table 13.

TABLE 13: Air quality standards for hydrogen fluoride and fluorides

Country and Standard	Value $\mu g/m^3$
1) Hydrogen Fluoride	
Canada, Maximum desirable level, 24 h	0.40
Canada, Maximum acceptable level, 24 h	0.85
Ontario, Air quality criteria, 24 h	0.86-3.44
U.S.A., Threshold limit value for workroom, 8 h	2000
New York State, Ambient air standard, 24 h	2.3
2) Fluorides	
U.S.A., Threshold limit value, 8 h	2500
U.S.S.R., Maximum allowable conc. for ambient air, 24 h	10
U.S.S.R., Maximum allowable conc. for ambient air, 1 h	30

1.3.3 Properties of Hydrogen Sulfide

There are a number of hydrogen sulfides, including polysulfides and hydrosulfides; however, hydrogen sulfide (H_2S) is the most common. Hydrogen sulfide is a colorless gas having the characteristic odor of rotten eggs. The gas is flammable, burning in air with a pale blue flame. The ignition temperature is 260°C. Mixtures in air between 4.3% and 46% by volume hydrogen sulfide are explosive.

Hydrogen sulfide is a liquid at minus 61.8°C and a solid at minus 82.9°C. The specific gravity of the gas is 1.189 when the specific gravity of the air is taken at 1.00. One liter of hydrogen sulfide at 0°C and 760 mm weights 1.5392 grams.

There is probably no odor more readily identifiable to the average individual than that of hydrogen sulfide. To most people, the odor of hydrogen sulfide is nothing more than an unpleasant nuisance. Yet, at higher concentrations, hydrogen sulfide is a deadly poison. It is nearly as toxic as hydrogen cyanide, and its action may be as rapid. Deaths due to hydrogen sulfide intoxication, which are reported regularly, are usually associated with exposure under occupation-related circumstances. Occasionally, however, they are consequent to accidental release of industrially generated hydrogen sulfide into the community.

Hydrogen sulfide is an irritant gas. Its direct action on tissues induces local inflammation of the moist membranes of the eye and respiratory tract. The dry surfaces of the skin are seldom affected by gaseous hydrogen sulfide, nor does the gas penetrate the intact skin to any significant extent. Most authors have found it convenient to categorize hydrogen sulfide poisoning under three rubrics according to the nature of the dominant clinical signs and symptoms. These rubrics are acute, subacute, and chronic poisoning.

- Acute intoxication:

  Effects of a single exposure to massive concentrations of hydrogen sulfide that rapidly produce signs of respiratory distress. Concentrations approximating 1,400 µg/liter (1,000 ppm) are usually required to cause acute intoxication.

- Subacute intoxication:

  Effects of continuous exposure to mid-level (140 to 1,400 µg/liter (100 to 1,000 ppm)) concentrations of hydrogen sulfide. Eye irritation is the most commonly reported effect, but pulmonary oedema has also been reported.

- Chronic intoxication:

  Effects of intermittant exposures to low to intermediate concentrations (70 to 150 µg/liter (50 to 100 ppm)) of hydrogen sulfide, characterized by "lingering", largely subjective manifestations of illness.

The establishment of standards for H_2S has often been difficult. Many critical decisions must be made regarding the extent of the relationships between various air pollution levels and their effects. Adverse effects in receptors must be defined. Range of resistance to H_2S must be established for men, animals and plants. Correlation of effects between species must be attempted. A standard for H_2S must be safe not only for the healthy adult but also for the aged, the young and the infirm. A distinction must be made between standards for ambient air and for workroom air. Because of all these difficulties, the air quality standards for H_2S vary significantly from country to country (Table 16).

TABLE 14: Physiological effects of hydrogen sulfide on man

Effects	Concentration	
	mg/m^3	ppm
Approximate threshold for odor	0.14-0.28	0.1-0.2
Offensive odor	4.2-7	3-5
Threshold limit value	14	10
Threshold of serious eye injury (gas eye)	70-140	50-100
Olfactory paralysis	210-350	150-250
Pulmonary oedema, imminent threat to life	420-700	300-500
Strong nervous system stimulation, apnea	700-1,400	500-1,000
Immediate collapse with respiratory paralysis	1,400-2,800	1,000-2,000

From: NATIONAL RESEARCH COUNCIL, Hydrogen Sulfide, PB-278 576, 1978.

TABLE 15: Poisoning accidents with hydrogen sulfide

Date	Place	Type of accident	Number of deaths and hospitalized	Reference
1925-1930	U.S.	Oil workers	59/	52
1943-1946	U.S.	Oil workers	0/14	↓
1966		Sewers workers	3/0	↓
24-11-1950	Poza Rica, Mex.	Oil refinery	22/320	18
~ 1970	Czechoslovakia	Viscose tank	10/?	53
01-12-1974	Abilene, Texas	Oil Pipeline	6/1	32
21-05-1974	Meridian, Miss.	Gas Pipeline	5/1	↓
26-08-1971	Berwich, Main	Tannery	6/0	↓

TABLE 16: Air quality standards for hydrogen sulfide

Location	Long-term[b]			Short-term[b]		
	mg/m^3	ppm	Averaging time	mg/m^3	ppm	Averaging time
Bulgaria	0.008[a]	0.005	24 hr	0.008	0.005	20 min
Canada						
(Alberta)	0.004	0.003	24 hr	0.014	0.009	1 hr
(Alberta				0.017	0.011	30 min
(manitoba)	0.017	0.001	24 hr	0.028	0.018	1 hr
(Newfoundland)				0.03	0.02	1 hr
(Ontario)				0.03	0.02	1 hr
(Québec)	0.002	0.005	2 hr			
(Saskatchewan)	0.007	0.005	24 hr	0.07	0.05	1 hr
Czechoslovakia	0.008	0.005	24 hr	0.008	C.005	30 min
Democratic Republic of Germany (East Germany)	0.008	0.005	24 hr	0.015	0.01	30 min
Federal Republic of Germany (West Germany)	0.15	0.1	30 min	0.3	0.2	30 min
	0.15	0.1	30 min	0.3	0.2	30 min
	0.02	0.013	30 min	0.05	0.03	30 min
Finland	0.05	0.3	24 hr	0.15	0.1	30 min
Hungary	0.15	0.1	24 hr	0.3	0.2	30 min
	0.008	0.005	24 hr	0.008	0.005	30 min
Israel	0.045	0.03	24 hr	0.15	0.1	30 min
Italy	0.04	0.03	24 hr	0.01	0.7	30 min
Poland	0.02	0.013	24 hr	0.06	0.4	30 min
	0.008	0.005	24 hr	0.008	0.005	30 min
Romania	0.001	0.006	24 hr	0.3	0.02	30 min
Spain	0.004	0.0025	24 hr	0.1	0.006	30 min
U.S.S.R.	0.008	0.005	24 hr	0.008	0.005	30 min
U.S.A.	0.008	0.005	24 hr	0.004 to 0.168[d]		
Yugoslavia	0.008	0.005	24 hr	0.008	0.005	30 min

(a) From: MARTIN and STERN, 1974, EPA-650-/9-75-001-a.
(b) The terms "short-term", if not otherwise stated, reflect only short or long averaging times.
(c) Underlined concentrations represent the values listed in legislation; others are approximate conversions.
(d) Depending on the state.

1.3.4 Properties of Sulfur Dioxide

Hydrogen sulfide is an inflammable gas which on burning will form sulfur dioxide (SO_2). For this reason, we must include in our considerations also SO_2.

Owing to the wide occurrence and peculiar properties of sulfur and sulfides, sulfur dioxide fumes have been known and utilized since earliest recorded history. Sulfur dioxide is one of the very minor and variable constituents of the atmosphere. Volcanic and other terrigenous gases contain on the order of 10% of sulfur-containing gases, largely sulfur dioxide and hydrogen sulfide. In some areas the amount of sulfur dioxide iin the atmosphere is increasing and reaches measurable concentrations as the result of heavy and widespread industrial activity.

Sulfur dioxide in the atmosphere is oxidized to sulfuric acid at a rate which depends on such factors as humidity, sulfur trioxide content, and particulate-matter concentration. Studies on the exhaust plumes from the stacks of coal-burning power plants and of smelters have shown oxidation rates for sulfur dioxide ranging from 0.1-2% min, depending principally on whether the humidity was low or high.

Sulfur dioxide is a colorless gas with a characteristic pungent choking odor. It condenses at -10°C at atmospheric pressure to a colorless liquid that freezes at -75.5°C. The molecular formula is SO_2, corresponding to a molecular weight of 64.06 in all its states. The critical temperature is 157.12°C and the critical pressure is 77.65 atm. At 0°C and 1 atm pressure, the gas has a specific gravity of 2.2636 relative to air occupies 341 ml/g, has a specific heat of 0.15 cal/g, and a dielectric constant of 1.0095. The gas is soluble to the

extent of 36 vols in water at 20°C, but is very much more soluble, several hundred to one by vol, in a number of organic solvents, such as camphor, acetone, and formic acid.

Sulfur dioxide is a relatively inert and stable gas that can be heated to about 2000°C without appreciable decomposition. It does not form flammable or explosive mixtures with air. Its stability is indicated by its high heat and free energy of formation, which are 70.9 and -69.7 kcal/mole, respectively.

Sulfur dioxide is a dangerous gas. It is toxic and extremely irritating on exposure for a short time. SO_2 is a skin irritant and a brief contact can cause inflammation and burns. Its effects on humans are summarized in Table 17. Air pollution standards for SO_2 have been established by the Environmental Protection Service in Canada, by the Environmental Protection Agency in United States and by other national and provincial agencies (Table 18).

1.3.5 Properties of Chlorine

Wherever chlorine is handled a potential risk is involved and a serious emergency might suddenly occur. Chlorine gas is primarily a respiratory irritant. Concentrations in air above 3 to 5 ppm by volume are readily detected by most persons. It causes varying degrees of irritation of the skin, mucous membranes, and the respiratory system, depending on the concentration and duration of exposure. In extreme cases death can occur from suffocation.

Acute non-lethal exposure to chlorine can cause various injuries, such as alveolo capillary injury, corneal burns, hemoptysis, eyanosis and pulmonary oedema. Other signs of chlorine intoxication are dyspnea, cough, retrosternal pain, headache, nausea and vomiting([49]).

TABLE 17: Physiological effects of sulfur dioxide on men

Concentration		Effects
ppm	mg/m^3	
0.2	0.6	First noticible odor.
5	15	Irritation of the nose and throat, accepted permissible level for prolonged exposure.
20	60	Eyes irritation.
50	150	Bronchospasm in some people, maximum permissible concentration for 1-hour exposure.
150	450	Extreme irritation of the nose, throat, lungs and eyes.
300	900	Nausea.
500	1500	Excessive exposure can cause death.
610	1830	Median lethal concentration for 1 hour
1350	4000	Median lethal concentraiton for 10 min

From: MEYER, B., Surfur, Energy and Environment, ELSEVIER, 1977, pp. 250-53.

and PATTY, F.P. (ed.), Industrial Hygiene and Toxicology, 1963, Vol. II, pp. 831-2307.

TABLE 18: Ambient air quality standards for sulfur dioxide

Country or province and standard	Averaging time	Value (g/m^3)
Canada, maximum desirable level	1 hr	450
Canada, maximum desirable level	24 hr	150
Canada, maximum desirable level	1 year	30
Canada, maximum acceptable level	1 hr	900
Canada, maximum acceptable level	24 hr	300
Canada, maximum acceptable level	1 year	60
Canada, maximum tolerable level	24 hr	800
Ontario	1 hr	690
Ontario	24 hr	275
Ontario	1 year	55
Saskatchewan and Alberta	1 hr	450
Saskatchewan and Alberta	24 hr	150
Saskatchewan and Alberta	1 year	30
Quebec, maximum average concentration	1 hr	1500
Quebec, maximum average concentration	24 hr	330
Quebec, maximum average concentration	1 year	60
U.S.A., maximum average concentration	5 min	1500
U.S.A., maximum average concentration	1 hr	600
U.S.A., maximum average concentration	24 hr	240
New York State, maximum average concentration	24 hr	300

TABLE 19: Physiological effects of chlorine on men

Concentration		Exposure	Effects
ppm	mg/m^3		
5	16	—	First noticable odor
10	30	1 hr	Bronchytis
15	45	—	Throat irritation
30	90	—	Coughing
50	160	30 min	Pulmonary oedema
100	320	5 sec	Stay in the contaminated air is intolerable
1000	3200	short	Death

From: FABRIC, R., "Toxicologie des gaz", Herman & Cie, 1943, J.S. Sconce, Chlorine: Its manufacture, properties and uses", Reinhold Publ. Corp., 1962.

Chlorine produces no known cumulative effects. Liquid chlorine produces no systemic effects, but when it vaporizes it will produce the effects described above. In contact with skin or clothing it may cause serious burns.

No systemic effects were detected in workers chronically exposed to chlorine. Sensitation has not been a problem with chlorine.

In the gaseous state, chlorine is greenish-yellow in color and is about 2.48 times as heavy as air; the liquid is amber-colored and is about 1.44 times as heavy as water. Unconfined liquid chlorine rapidly vaporizes to gas; one volume of liquid yields about 450 volumes of gas. Chlorine is only slightly soluble in water.

Under specific conditions chlorine reacts with most elements, sometimes with extreme rapidity. Because of its great affinity for hydrogen, chlorine removes hydrogen from some of its compounds, such as the reaction with H_2S to form hydrochloric acid and sulfur.

Most common metals are not affected at normal temperatures by dry chlorine, either gas or liquid; but moist chlorine is very corrosive to all common metals. It can be handled in stoneware, concrete, glass, and procelain equipment and by certain specialized alloys. Additionally, hard rubber, unplasticized polyvinyl chloride and Teflon have been used successfully.

Chlorine can be absorbed in solutions of caustic soda; 1.25 g of caustic soda is needed to neutralize each gram of chlorine. Chlorine leaks should be investigated immediately and the situation should corrected promply. Water should be never used on a chlorine leak as it makes the leak worse due to the corrosive effect.

1.4 Fire and Explosion Hazards

The most important fuels used at facilities involved in nuclear fuel cycle are gasoline, diesel and heating oils, which may cause fires when improperly handled. Consequences of these fires, which may be important as far as workers are concerned, present in our opinion very little hazard to the public. We believe that the probability that a fire originating at such facility would propagate to a community near by is negligible.

The same conclusions can be made for explosifs. These are used only at mines and in very safe way. The explosive mixtures are prepared for each blasting([21]) and cannot present a danger to the

public. Should an explosion occur, the consequences to the public would be low when considering distance which separates the mine and nearest dwellings.

1.5 Population at Risk

Due to the scope of this study, it is not feasible to establish and use in calculations detailed population distribution around each nuclear facility. It would be also difficult to study in detail corridors used for the transport of hydrogen sulfide to heavy water plants, ammonia, a hydrogen fluoride to the refinery and sulfuric acid and lime to mines. Consequently, we have used throughout this study a single value for the population density of 25 persons/km^2. This figure was selected because it close to the population density for United States (22 persons/km^2) and we believe it is reasonably representative for the population density of the southern strip of Canada.

1.6 Treatment of Errors

No measured value or calculated result is absolutely accurate but it is subject to a certain error. The error itself may not be known accurately and it becomes necessary to establish a standard deviation for each value used in calculations. In this section we will describe the treatment and propagation of errors. In order to estimate uncertainty for transportation accidents we have used CONSAD data cited by Rowe([23]) and calculated the relative standard deviations assuming Gaussian distribution for number of catastrophic events in U.S. from 1953 to 1973:

- Highway accidents : σ = 100%
- Railroad accidents : σ = 67%
- Commercial aviation : σ = 40%

These uncertainties will be used in conjunction with their corresponding probabilities to estimate the overall incertainty for the hazard of the type H_2. Distances, quantity used and probabilities of different weather categories are known with relatively high prevision and we assumed that the relative standard deviations are negligible.

The precision of results for the poisoned areas is unknown. Results are highly dependent on the plume rise, wind speed, weather category and other factors and it becames very difficult to estimate their precision. In our bibliographical research we did not found any model for treatment of uncertainties in the calculation of atmospheric dispersion. Therefore it can be only stated that the overall error is greater than the stated one. It appears desirable to develop a model for treatment of uncertainties in the calculation of the poisoned areas.

The precision of the probability of failure of pressure vessels is also unknown. According to T.A. Smith([9]) the 99% confidence upper bound for catastrophic failure ranges from 2.7 E-6 to 4.6 E-4 failures per vessel year, and the figure of 1 E-4 should be used. No information about precision of this figure is given. When the precision of the controlling value in a given calculation is unknown the symbol $\underline{\pm u}$ will used to describe the overall error of the result.

We have not found any formula explicitely stating the uncertainty for the seismic risk and for this reason it will be indicated as "unknown" in our results.

The precision of the probability of occurence of a leak in a heavy water plant is also unknown. One possible approach which can be used to obtain better data would be to study the number a magnitudes of

small leaks occuring in heavy water plants or in similar installations such as oil refineries. Such study should generate a good statistical data from which the probability distribution for the number of leaks versus their magnitude could constructed. This distribution function could be extrapolated in order to estimate the probability of occurence of large leaks which are presently known with low accuracy and precision.

It would be also desirable to have some data on the frequencies of human errors commited by workers in heavy water plants or refineries. In order to estimate these it would be necessary to analyze the accident records in both industries.

Carson and Mumford([43]) analyzed incidents involving major hazards in the chemical industry. From this analysis it is possible to obtain data on chlorine releases from 1914 to 1977:

Magnitude of release (Mg)	< 1	1-9	10-19	20-29	30-39	> 40
Number of releases	7	12	6	6	1	1

Decade of release	1910-9	1920-9	1930-9	1940-9	1950-9	1960-9	1970-9
Number of releases	2	5	4	5	5	8	4

This gives an average of 0.52 ± 0.08 releases per year and the relative error of 15% will be used in the calculation of uncertainty for the fixed installations (type H_1).

In order to estimate the propagation of errors during additions and multiplications we have used the following well-known formulas:

$$x = au \pm bv \; : \; \sigma_x^2 = a^2\sigma_u^2 + b^2\sigma_v^2 + 2\,ab\,\sigma_u^2 \qquad \ldots (1.42)$$

$$x = auv \qquad : \frac{\sigma_x^2}{x^2} = \frac{\sigma_u^2}{u^2} + \frac{\sigma_v^2}{v^2} + \frac{\sigma_{uv}^2}{uv} \qquad \ldots (1.43)$$

where σx, σu, σv are the standard deviations of functions x, u or v and a, b are constants.

The variability of accident rates of railway or highway transportation can be easily calculated from the data published annually by the Statistics Canada([8],[50]). Therefore we obtain the following standard deviations for the hazard of the type H_3:

- Railways : σ = 20%
- Highways : σ = 8%

As can be seen the variability of the "ordinary accidents" is much smaller than for the catastrophic ones (type H_2). The same standard deviations will be used for fatalities and injuries.

2. URANIUM MINING AND MILLING

The potential hazards to the public due to the uranium mining are fires, explosiions, poisoning by toxic chemicals released from the plants and fatalities due to the transportation of materials to and from the plant.

Uranium mills use kerosene during the processing of ore and fuel oil for heating. These substances represent a certain fire danger. But we believe that due to the distance which separates usually the plant and nearest dwelling, the danger from the fire to general public is negligible.

Explosifs (ammonium nitrate mixed with fuel oil) are used in mines for blasting. If improperly treated, these can present a hazard to miners but not to the public. Consequently we feel that danger from explosions is also negligible.

Uranium mills use large amount of chemicals to treat the ore. The most important ones are sulfuric acid, nitric acid, lime, ammonia and sodium chlorate. All these chemicals are relatively safe solids or liquids and in case of an accident, they would diffuse through the air very slowly and do not present, in our opinion, a hazard to the public; consequently, $H_1 = 0$. These chemicals do find their way into effluents and may present some danger to aquatic life but if we assume that people living in the proximity of an uranium mill do not drink the plant effluents or do not use them for their washing and cooking, very little harm would be done to them.

Atmospheric non-radioactive emissions from the mill include NO_x, SO_2 and particulates. At Elliot Lake, their concentrations 2 km down-wind from mill vary from 420 to 775 $\mu g/m^3$ for SO_2, from 86-205 $\mu g/m^3$ for NO_x, and from 32-410 $\mu g/m^3$ for particulates([21]). These concentrations are within Canadian air quality objectives. The people around the mill are exposed to the typical "industrial" air and its health effects should be similar to those in any large city.

The public in general is exposed to certain hazard because of transportation of large amounts of chemicals to the plant and to some degree, the delivery of the product (yellowcake). The estimated reagent usage per 1 kg or U_3O_8 at Denison Mill at Elliot Lake is shown below([21]):

- Sulfuric acid (93%)	:	31 kg
- Nitric acid (60%)	:	3 kg
- Lime	:	24 kg
- Sodium chlorate	:	0.7 kg
- Others	:	0.6 kg
T O T A L	:	59.3 kg

As in a first approximation, we will consider only bulk chemicals used, namely sulfuric acid and lime. According to the Ministry of Industry, Trade and Commerce([24]), the producers of these two chemicals which are located relatively close to Elliot Lake are the following companies:

Producers of sulfuric acid:	Distance (km)
- International Mineral & Chemical Corp.	640
- Falconbridge Nickel Mines, Sudbury, Ont.	160

Producers of lime:	Distance (km)
- Domtar, Beachville, Ont.	600
- The Steel Company of Canada, Hamilton, Ont.	608

The trucking distances adopted are 160 km in the case of sulfuric acid and 600 km for lime. If we assume that acid is shipped in 9 m^3 tanks which contains 16.6 Mg of acid, we can calculate the number of fatalities and injuries by using formula (1.30). If we apply figures cited, we will obtain following estimates for hazard due to the transportation (per kg of U_3O_8).

Chemical	Sulfuric acid	Lime	Total
Injuries	5.4 ± 0.4 E-8	1.6 ± 0.1 E-7	2.1 ± 0.1 E-7
Deaths	1.5 ± 0.1 E-9	4.3 ± 0.3 E-9	5.8 ± 0.3 E-9

Uranium producton capacity in Elliot Lake area (Denison Mines and Rio Algom Mines) in 1976 was approximately 13,800 Mg per day[25] which translates into the annual production rate of 4 Gg of U_3O_8. This means that the overall imputed hazard due to the uranium mining at Elliot Lake amounts to 0.8 ± 0.1 injuries and 2.3 ± 0.2 E-2 fatalities per year. According to Critoph[26], 133 Mg of uranium are needed to produce 1 GWy of electricity. This is equivalent to 157 Mg of U_3O_8 which would result in 3.3 ± 0.3 E-2 injuries and 9.1 ± 0.7 E-4 fatalities.

TABLE 20: Hazards due to uranium mining

Type of hazard	H_1	H_2	H_3
Fatalities	0	0	9.1 ± 0.7 E-4
Injuries	0	0	3.3 ± 0.3 E-2

3. URANIUM REFINING

After mining and milling, uranium must be further purified in order to be suitable as a reactor fuel. This purification is done at a single canadian refinery of uranium at Port Hope, Ontario. The crown corporation, Eldorado Nuclear Ltd., is in charge of uranium refining. Its present plant at Port Hope has a capacity of a 3860 Mg of uranium hexafluoride (UF_6) per year which should be increased to 13,300 Mg in 1986. This is equivalent to 2610 Mg of uranium metal.

A schematic of uranium refining is shown in Figure 2. Yellowcake is received in 205 litre steel drums. After sampling and analysing, yellowcake is treated with nitric acid in a staged digestion process to produce a crude uranyl nitrate. The crude uranyl nitrate solution then proceeds to solvent extraction which uses multi-stage extraction columns. In the first stage, the uranyl nitrate solution is introduced at the top of the column while the solvent solution, tributyl phosphate (TBP) in kerosene, is introduced near the bottom. The uranium transfers to the solvent phase, leaving the majority of its impurities in the aqueous phase. In the second solvent extraction stage, the uranium-bearing organic phase is washed with small volume of water. In the third stage, the uranyl nitrate is re-extracted back to the aqueous phase and is concentrated by evaporation.

The concentrated uranyl nitrate is thermally decomposed in denitrators to uranium trioxide (UO_3), UO_3 is reduced to uranium dioxide (UO_2) by reacting it with hydrogen. The hydrogen is produced either by dissociation of anhydrous ammonia or as by product in fluorine generation. UO_2 may be sent either to the fuel fabrication plant or may be converted to uranium tetrafluoride (UF_4) by reaction with

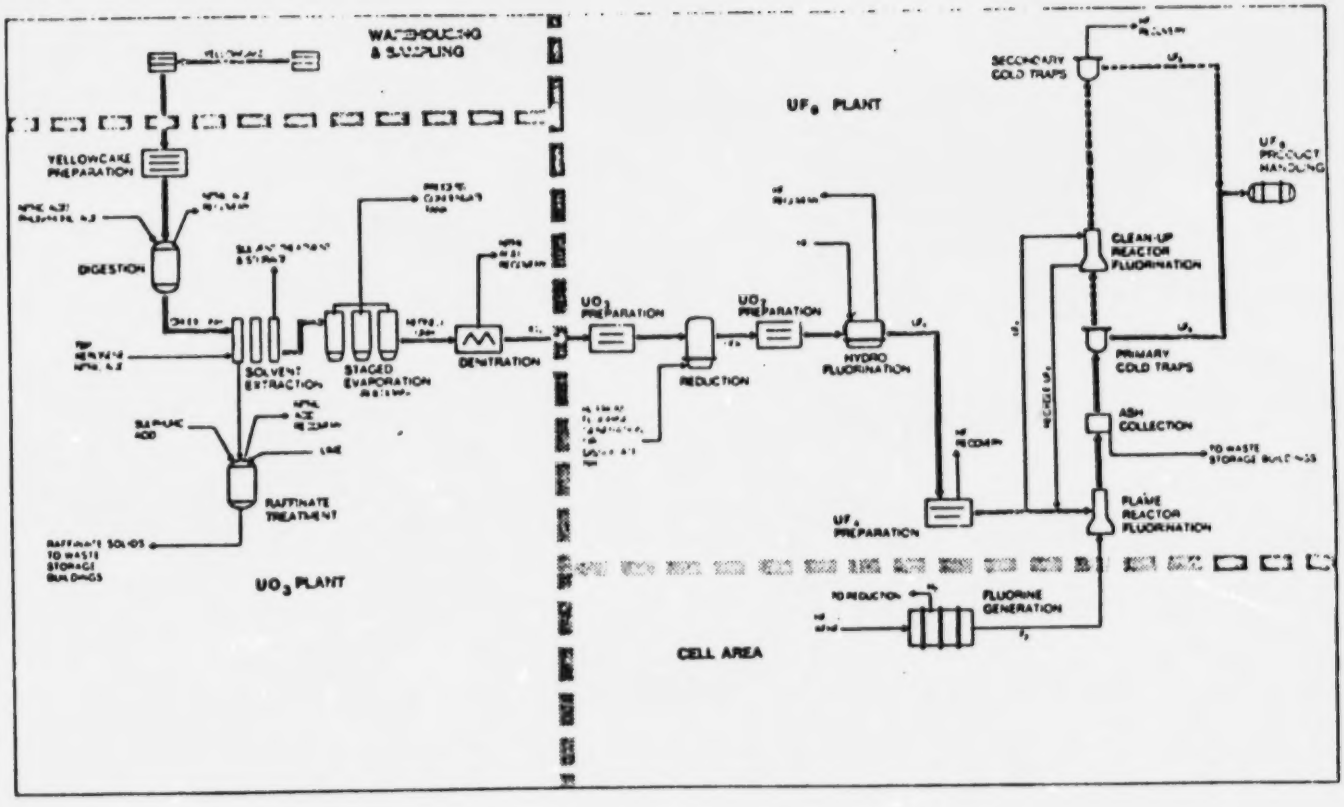

FIGURE 2: UF_6 Process Schematic

(Courtesy Eldorado Nuclear Ltd)

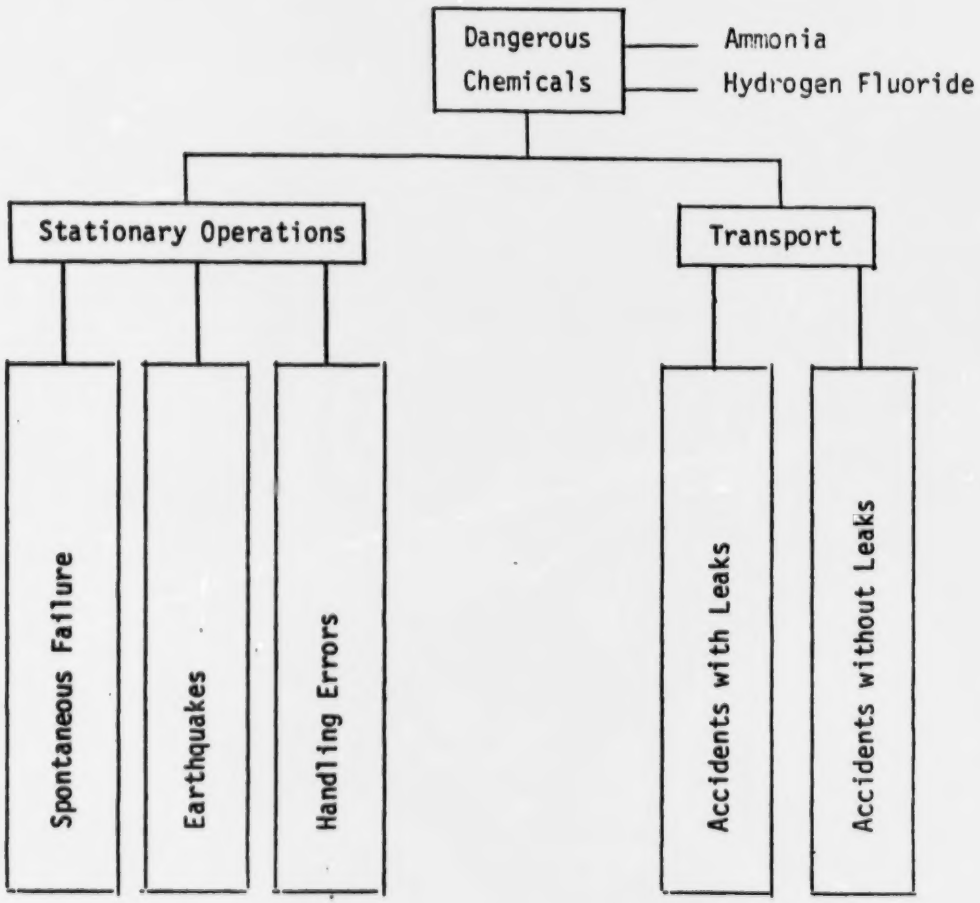

FIGURE 3: Schematics of Chemical Hazards from Refineries

hydrogen fluoriode (HF). Prepared UF_4 is fed to a flame reactor with the fluorine gas to convert it into uranium hexafluoride (UF_6). Fluorine is produced by electrolysis of HF in high amperage low voltage electrolytic cells. UF_6 is recovered in cold traps and packed in thick-walled steel shipping cylinders. These cylinders hold either 9 or 13 tonnes of UF_6.

There are several chemical reagents used in refining of the yellowcake which may constitute a hazard for the public. The most important are hydrogen fluoride, fluorine, uranium hexafluoride and anhydrous ammonia. Hydrogen fluoride is shipped to the plant in rail cars (0.18 vehicles per day) while other chemicals are shipped by trucks.

Let's first establish the material balance for dangerous chemicals used in refineries of uranium. The chemical reactions which take place are:

$$UO_3 + H_2 \rightarrow UO_2 + H_2O \quad \ldots (3.1)$$

$$UO_2 + 4\ HF \rightarrow UF_4 + 2\ H_2O \quad \ldots (3.2)$$

$$2\ HF \rightarrow H_2 + F_2 \quad \ldots (3.3)$$

$$UF_4 + F_2 \rightarrow UF_6 \quad \ldots (3.4)$$

From stochiometry it can be easily calculated that 7 g of H_2 or 42 g of NH_3 are used in order to obtain 1 kg of UO_2 and 340 g of HF in order to produce 1 kg of UF_6. These data make possible the calculation of amounts of dangerous reagents consumed per unit of the product. We can

also calculate the annual consumption of important chemicals for present annual capacity of 3860 Mg of UF_6. The annual requirements will be 1312 Mg of hydrofluoric acid and 123 Mg of ammonia. A schematics of different scenario considered is shown in Figure 3. Consequences of the release of HF or NH_3 depend strongly on tamospheric conditions during release.

The probabilities of different weather categories in Port Hope area were established by MacLaren Ltd.([21]) and are summarized in the following table.

TABLE 21: Probability of occurrence of different weather categories([19])

Class	A	B	C	D	E	F
Probability	0.5	4.4	9.3	63.3	9.5	13.0

The wind directions and speeds are measured by Environment Canada at many stations across Canada. Unfortunately, there is no station at Port Hope but we believe that data obtained at Peterborough may be used also for Port Hope area. These data are listed in Table 23.

Different types of hazard claculated in the following two sections are summarized in Table 22.

TABLE 22: Hazards due to uranium refining

Type of hazard	H_1	H_2	H_3	Total
NH_3 (deaths/y)	3.6 ± 0.5 E-4	5.5 ± 5.5 E-5	8.9 ± 0.7 E-6	4.2 ± 0.5 E-4
NH_3 (injuries/y)	4.0 ± 0.6 E-3	1.8 ± 1.8 E-3	3.3 ± 0.3 E-4	5.8 ± 1.9 E-3
HF (deaths/y)	6.6 ± 1.0 E-3	1.2 ± 0.8 E-2	6.8 ± 1.4 E-4	1.9 ± 0.8 E-2
HF (injuries/y)	1.8 ± 0.3 E-2	4.0 ± 2.6 E-1	1.7 ± 0.3 E-3	4.2 ± 2.6 E-1

TABLE 23: Prevailing wind directions and wind speed classes at Peterborough, Ont.

1979	Prevailing direction	Mean speed km/h	Speed classes (%) km/h					
			0	1-5	6-11	12-19	20-28	29-38
January	SVL	13.6	12	9	24	32	19	3
February	NW	11.4	15	12	29	29	12	3
March	WNW	11.5	18	12	27	22	16	5
April	WNW	13.8	11	10	26	28	20	4
May	WNW	10.7	18	9	32	26	14	1
June	S	10.9	22	8	25	28	16	1
July	S	7.7	24	18	33	21	4	—
August	W	8.0	24	18	33	17	7	1
September	SSW	8.0	25	14	32	22	7	—
October	NW	9.7	18	11	33	30	8	4
November	W	9.9	19	15	32	21	9	3
December	SW	12.1	10	12	31	30	14	3
Annual Average (%)	—	10.6	18	12	30	26	12	2.3
Speed (m/s)	—	3	0	0.8	2.4	4.3	6.7	9.3

Now we must distinguish two cases: uranium will be used in CANDU reactors or in light water reactors. In the case of CANDU reactors hazards due to the hydrogen fluoride don't apply and hazard figures will be 4.2 ± 0.5 E-4 deaths and 5.8 ±1.9 E-3 injuries in order to produce 2961 Mg of UO_2. According to Critoph([26]), 133 Mg of uranium are needed to produce 1 Gwy of electricity. This is equivalent to 151 Mg of UO_2. Consequently, the hazard figures for CANDU reactor will be 2.1 ±0.3 E-5 deaths and 2.9 ± 1.0 E-4 injuries per 1 Gwy. In the case of light water reactor hazard due HF must be added. For this type of reactor, annual uranium requirement is 160 Mg per 1 GWy of electricity ([76]). This amounts to 182 Mg of UO_2 and hazard to the public will be 1.2 ± 0.5 E-3 deaths and 2.6 ± 1.6 E-2 injuries.

3.1 Hazard due to anhydrous ammonia

Anhydrous ammonia (NH_3) is used at Port Hope refinery as a source of hydrogen. Ammonia is a colorless, toxic and flammable gas. According to Leblanc([27]), flammable limits of NH_3 in air are 16-25%.

Ammonia is normally shipped and stored in the liquid form. Dry ammonia is not corrosive to most metals. Moisture addition however makes it corrosive to some metals and some potential accidents may be caused by this effect. Liquid ammonia has density of 0.6 g/ml and it boils at -33°C at atmospheric pressure. Ammonia is a reactive chemical, which will readily oxidize in the presence of the air. Reducing agents normally do not react with ammonia.

Ammonia is delivered to the Port Hope refinery by tank trucks. Capacity of these can vary from 23 to 30 m^3([27]).

Major credible accidents involving NH_3 are spill during the transportation to the plant or during handling of ammonia at refinery. Some of possible accidents are spontaneous pipe failures, explosion and breach of containers, and a failure to close valves of the truck tanker or storage tanks.

Pressure vessels and pipes could also fail due to "stress corrosion". The probability of this type of failure was estimated to be 10^{-4} per year([9]). Probabilities of an earthquake and airplane crash are much samller and can be neglected. The largest amount which can be released is approximately one truck shipment or 18 Mg of liquid ammonia. Consequences of such release depend on the wind direction, wind speed, weather conditions (Tables 21 and 22) and population density in the affected sector.

According to Fryer, Kaiser and Walker([9]), a rough estimate for the concentration of ammonia which is potentially fatal for exposures of the order of 30-50 mintues is 2 g/m^3. We have used the lower time value of 30 minutes which gives the integrated fatal exposure of 3600 gs/m^3. This value was used in the computer program INRL which calculates the distances at which fatal exposure should occur and the extent of the poisoned area. This program was run for 3 weather categories and results are listed in the follwing table.

TABLE 24: Consequences of instantaneous release of 18 Mg of ammonia

Weather category	Unstable	Neutral	Stable
Probability of occurence (%)	5	73	22
Wind speed (m/s)	2	3	2
Lethal area (km^2)	0.00	0.00	0.66
Harmful area (km^2)	0.00	0.25	6.43

Notes: Lethal exposure = 3600 gs/m^3
Harmful exposure = 600 gs/m^3

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Using the values in Table 24 and assuming the population density of 25 persons/km^2, we can calculate the overall hazard to the population which is equal to:

$$H_1 = 1\ E\text{-}4 * 0.22 * 0.66 * 25 = 3.6 \pm 0.5\ E\text{-}4 \text{ deaths/year}$$

For injuries we will obtain:

$$H_1(1) = 1\ E\text{-}4 * (0.25 * 0.73 + 6.43 * 0.22) * 25$$
$$= 4.0 \pm 0.6\ E\text{-}3 \text{ injuries/year}$$

Another hazard to the public from ammonia is due to its toxicity and the transport to the refinery. The minimum annual consumption (assuming no losses) of ammonia is 123 Mg and we will use in our calculation this figure. We assume also that average unit shipment of this chemical by the truck tanker is 18 Mg from which follows that there are at least 7 shipments per year. According to Ministry of Industry, Trade and Commerce publication([24]), there are 11 canadian producers of ammonia. Producers of ammonia which are close to the Port Hope refinery are the following companies:

Company and location:	Distance to the Port Hope (km)
- Canadian Industries Ltd., Court Wright, Ont.	496
- Cyanamid Canada, Niagara Falls, Ont.	264
- Genstar Chimie Ltd., Maitland, Ont.	256

For the purpose of this study, we assumed a trucking distance of 260 km. We did not found any statistics for ammonia tanker accident rates but we believe that the figure cited by Fryer([9]) for the probability of accidents involving leaks for petroleum tankers (1.6 E-8 events/ km) can also be applied to the transportation of ammonia.

Number of expected deaths per accident in urban and rural environments was studied by Kalelkar, Partridge and Brooks([14]) for a number of substances including ammonia. They list the following values.

- Relative exposure urban environment : 23%
- Relative exposure rural environment : 77%
- Expected death per accident in a city : 7.3
- Expected death per accident in the countryside : 0.29

Now we can combine all figures shown above and calculate the hazard to public which is equal to:

$$H_2 = 7 * 1.6\ E\text{-}8 * 260 * (0.23 * 7.3 + 0.77 * 0.29)$$
$$= 5.5 \pm 5.5\ E\text{-}5 \text{ deaths/year}$$

There are on the average 33 injuries for each death([50]) and therefore we obtain:

$$H_2(i) = 5.5\ E\text{-}5 * 33 = 1.8 \pm 1.8\ E\text{-}3$$

Finally, we can calculate the "physical" hazard due to the accidents involving trucks with ammonia in which there are no leaks and the toxicity of ammonia is not the cause of the harm.

For deaths, we will have:

$$H_3 = 4.9\ E\text{-}9 * 7 * 260 = 8.9 \pm 0.7\ E\text{-}6 \text{ deaths/year}$$

or $$H_3' = 8.9\ E\text{-}9 / 2.6\ E\text{-}9 = 3.4 \pm 0.3\ E\text{-}15 \text{ deaths/g of U}$$

For injuries, we obtain:

$H_3(i)$ = 1.8 E-7 * 7 * 260 = 3.3 ± 0.3 E-4 injuries/year

or $H_3'(i)$ = 3.3 E-4 / 2.6 E-9 = 1.3 ± 0.3 E-13 injuries/g of U

3.2 Hazard Due to Hydrogen Fluoride

Hydrogen fluoride (HF) is used in refineries to convert uranium dioxide to uranium tetrafluoride and as feedstock for production of fluorine. 340 grams of HF are needed to produce 1 kg or uranium hexafluoride which means that its annual consumption at Port Hope is 1312 Mg. Hydrogen fluoride is delivered to the refinery at Port Hope in rail cars at a rate of 0.18 cars per day. From rail terminal HF is transfered to a storage area. According to Gall([51]), the capacity of railroad cars which are used in transport of HF, vary from 20-91 Mg of HF. For converative purposes the 20 Mg figure has been used.

The first type of accident which can occur is the major leak during transfer from the rail car to the storage tanks or pipe breakage. The probability of an handling error of similar nature was estimated to be 1 E-4 events/year([9]). In our calculations, we will use this figure.

The technical problems in judging hazard of hydrogen fluoride (HF) are very complex. The molecules of HF polymerise and form a hexameric species $(FH)_6$. Behavior of such polymer is completely different from its monomer (HF). While the monomer has a low molecular weight and should be buoyant, the hexamer should behave as a heavier than air gas like for example chlorine. Degree of polymerization of HF depends on the temperature and partial pressure (concentration). High

temperatures and low concentrations favour the monomer while the reverse conditions favour the hexamer. Furthermore, the dissociation of hexamer is an endothermic process requiring 300 cals/g which may be furnished for example by the solar heating. The atmospheric dispersion of HF was analysed by Beattie, Abbey, Haddock and Kaiser([9]). They have reached the following conclusions. If HF behaves like a monomer, even a large instantaneous release of 150 Mg of HF does not represent a danger for E and D weather classes. If the HF has dispersion characteristics similar to those of chlorine, an instantaneous release of 20 Mg of HF during class D weather conditions does constitute a hazard with a lethal range of 2.7 km([9]).

We have used our computer program to calculate the areas where lethal and harmful concentrations of HF would occur and the consequences of an instantaneous release of 20 Mg of HF are shown in the following table.

TABLE 25: Consequences of an instantaneous release of 20 Mg of HF

Weather	Unstable	Neutral	Stable
Probability (%)	5	73	22
Wind speed (m/s)	2	3	2
Lethal area (km^2)	0.05	0.44	10.5
Prob.* area (km^2)	0.003	0.32	2.31
Harmful area (km^2)	0.26	1.58	27.1
Prob.* area (km^2)	0.01	1.15	5.96

Notes: Fatal exposure : 450 gs/m^3
Harmful exposure : 150 gs/m^3

Risks to the public due to the presence of HF at Port Hope refinery will be:

$$H_1 = 1\ E\text{-}4 * (0.03 + 0.32 + 2.31) * 25$$
$$= 6.6 \pm 1.0\ E\text{-}3 \text{ deaths/year}$$

$$H_1(i) = 1\ E\text{-}4 * (0.01 + 1.15 + 5.96) * 25$$
$$= 1.8 \pm 0.3\ E\text{-}2 \text{ injuries/year}$$

Another scenario which can be considered is a relcase at a rate of 10 kg/s. By using the progam PLR the values for the lethal and harmful areas where the concentration of HF exceeds 2 and 0.1 g/m^3 resp. can be calculated (Table 26).

TABLE 26: Consequences of the continuous release of HF at a rate of 10 kg/s

Weather	A	B	C	D	E	F
Probability (%)	5	4.4	9.3	63.3	9.5	13
Wind speed (m/s)	1	2	3	5	2	1
Lethal area (km^2)	0.0	0.0	0.0	0.0	0.0	0.2
Prob.* area (km^2)	0.0	0.0	0.0	0.0	0.0	0.03
Harmful area (km^2)	0.0	0.04	0.21	0.47	1.75	11.5
Prob.* area (km^2)	0.0	0.002	0.02	0.30	0.17	1.50

Consequently we will obtain:

$$H_1 = 1\ E\text{-}4 * 0.03 * 25 = 7.5 \pm 1.1\ E\text{-}5 \text{ deaths/year}$$

$$H_1(i) = 1\ E\text{-}4 * (0.002 + 0.02 + 0.30 + 0.17 + 1.50) * 25$$
$$= 5.0 \pm 0.8\ E\text{-}3 \text{ injuries/year}$$

Another scenario which will be considered is the major catastrophy such as a crash of a heavy airplane. The consequences of such event would be a quasi-instantaneous release of hydrogen fluoride. Inventory of HF in the refinery may vary during the year but let assume that amount released is 150 Mg or approximately one-tenth of annual consumption.

According to Beattie, Abbey, Haddock and Kaiser([9]) such release would be lethal to distance of 8 km if we assume that HF disperses like chlorine. For class D weather conditions the poisoned area would cover 5.5 km^2 and the hazard would be is equal to:

$$H_1 = 1.5\ E\text{-}7 * 0.63 * 5.5 * 25 = 1.3 \pm 0.5\ E\text{-}5\ \text{deaths/year}$$

This hazard is much smaller than hazard due to handling errors and can be neglected.

Another hazard which needs to be considered is the transportation hazard due to the toxicity of HF. Assuming a unit shipment of 21 Mg, 64 shipments are needed to satisfy the annual consumption of 1312 Mg of HF. According to Ministry of Industry, Trade and Commerce publication([24]), there are only few producers of hydrogen fluoride in Canada and closest to Port Hope refinery ar two plants of Allied Chemical Canada Ltd. one located at Amhersburg, Ont. and the other one at Valleyfield, Que. The distance from the plants to Port Hope is 495 km and 464 km respectively. A probability of a serious derailment in Canada is 2.6 E-8 events/km([8]).

We did not find any data on the expected number of fatalities per accident. But data are available for chlorine which has presumably similar dispersion characteristics. Kalelkar, Partridge and Brooks published([14]), the impact value for rail transportation of chlorine which is 15.7 deaths/accident.

Now, we can calculate the hazard to public:

H_2 = 2.6 E-8 * 64 * 464 * 15.7 = 1.2 ± 0.8 E-2 deaths/year

Knowing that there are on the average 33 injuries for each death([50]) we obtain:

$H_2(i)$ = 1.2 ± 0.8 E-2 * 33 = 0.40 ± 0.26 injuries/year

The figure of 1.2 E-2 deaths/year can be compared with risk assessment figures derived by Franklin, Rhoads and Andrews([29]) for chlorine transportation.

They have found that there are on the average 2 E-4 deaths/ shipment or 4 E-7 deaths/km. If we use these figures, we will obtain:

H_2 = 64 * 2 E-4 = 1.3 E-2 deaths/year

H_2 = 64 * 464 * 4 E-7 = 1.2 E-2 deaths/year.

Both results agree well with the result obtained earlier. Hazards H_3 and $H_3(i)$ can be calculated in the same way as for ammonia:

H_3 = 2.3 E-8 * 64 * 464 = 6.8 ± 4.6 E-4

H_3 = 5.6 E-8 * 64 * 464 = 1.7 ± 1.1 E-3

As mentionned previously, no data were found on the expected number of fatalities as a result of an accident of a tanker carrying hydrogen fluoride. For this reason it apprears desirable to study safety record of installations using hydrogen fluoride and to establish reliable statistical data which could be used in the future risk assessment studies.

4. ASSESSMENT OF HAZARD DUE TO THE OPERATION OF HEAVY WATER PLANTS

As chemical, used in heavy water production which represents the greatest danger for the public is, in our opinion, H_2S. The possible consequences for the public due to the release of H_2S were calculated using the logical diagram shown in Figure 4. In order to quantify the danger for the public, it is necessary:

1) to establish the probability of a leak of H_2S of a given magnitude and given nature;
2) to establish the probability of ignition of H_2S;
3) to establish the reliability of the dispersion system;
4) to know the average atmospheric conditions for different wind directions and the topography around the plant;
5) to know the distribution of the population around the plant and to know the effect of H_2S on humans.

With this knowledge, we can calculate the probability of occurrence of given ground level concentration of H_2S around the plant and its possible consequence for the safety of the public.

The most difficult part of risk assessment for heavy water plants is the establishment of probability of leaks of a given magnitude. There are several possible approaches to this problem. The first and the best known method is the "fault tree" analysis. This technique consists basically of identifying all possible accidents which may occur and establishing the sequence of events which may lead to a given accident. In order to use this method, it is necessary to know very well the plant and probabilities of occurrence of differents faults.

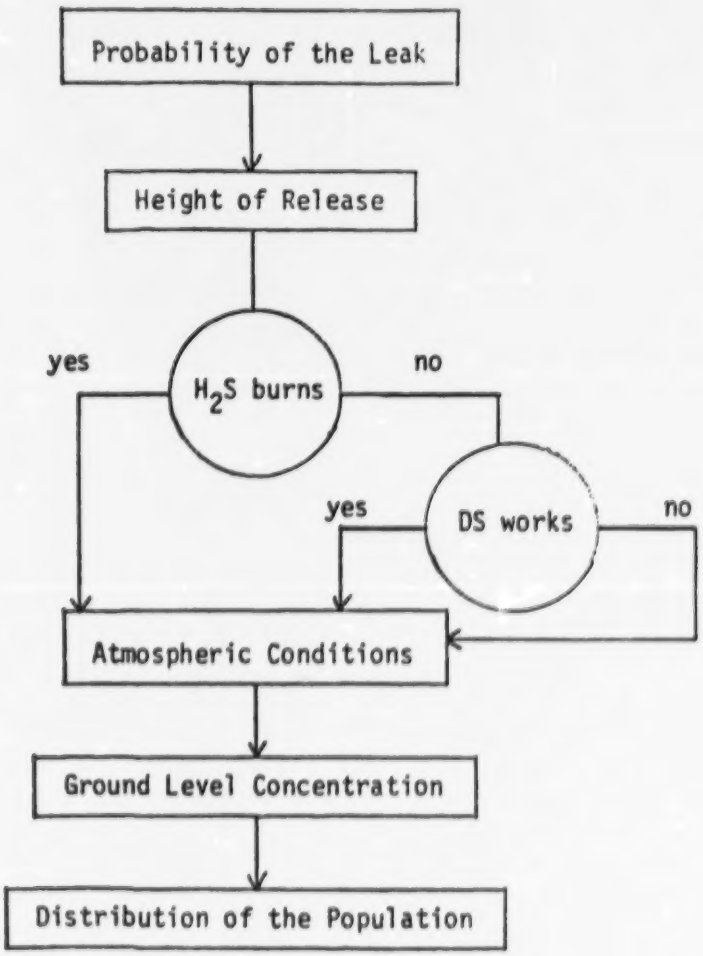

FIGURE 4: Risk Assessment Methodology for Heavy Water Plants

Notes: DS = Dispersion system (when applicable)

The fault tree analysis is a very time consuming technique which necessitates a large engineering staff which is not available for this study. Another possible approach is to use statistics on accidents and their consequences for existing heavy water plants. But operating experience is limited in this regard. The only plants which operated for a significant lapse of time are ([30]):

Site	Capacity Mg/y	Start-up year
- Savannah River, U.S.A.	190	1952
- Port Hawkesbury, Canada	360	1970
- Bruce A, Canada	720	1973
- Glace Bay	360	1976

These plants have operated safely and there was no accident serious enough to cause the harm to the public. This experience can be used to estimate the upper limit of the probability of an important leak which would cause fatalities or injuries.

Considering that these 3 plants accumulated up to 1981, 53 years of operating experience, we can only state that the probability of a serious accident (assuming a binomial distribution) should be lower than 0.43/year/plant at a 90% confidence level.

Another approach which can be used to estimate the hazard to the public of heavy water plants is to draw an anology with other industries using H_2S. Hydrogen sulfide is used to prepare various inorganic and organic sulfur compounds or is a by-product or waste from a number of industrial operations.

In the production of carbon disulfide, sulfur is reacted with natural gas at elevated temperatures. Half of the sulfur introduced is consumed in the production of hydrogen sulfide. Depending on the sulfur content of the basic raw material, substantial quantities of hydrogen sulfide can be released during the production of coke or of manufactured gases from coal.

The process for making thiophene requires the reaction of sulfur with butane at elevated temperatures. This reaction also produces hydrogen sulfide.

In the manufacture of viscose rayon, cellulose pulp is treated with sodium hydroxide, then with carbon disulfide, and again with sodium hydroxide to produce the viscose solution. The viscose solution after spinning or coating is passed through a series of acid coagulation baths where hydrogen sulfide is released. From 6 to 9 kg of hydrogen sulfide are formed per 100 kg of rayon produced.

During all these processes, danger from H_2S exists. It is thus possible to compile the actual accidents involving H_2S which happened in the past and the quantity of H_2S manipulated and to calculate the probability of a large release of the gas resulting in death for members of the public. The following poisoning accidents with H_2S happened recently:

Date	Place	Type of accidents	Number of deaths	Reference
24-11-1950	Poza Rica, Mexico	Oil refinery	22	18
21-05-1974	Meridian, Miss., US	Gas pipeline	5	32

These accidents account for 27 fatalities. Not included in these fatalities are deaths of workers manipulating H_2S; 24 such fatalities were reported worldwide from 1950 to 1980.

According to Macaluso([31]), the worldwide recovery of H_2S in 1955 amounted to 6600 Gg. If we assume this to be an average yearly usage of H_2S, the probability of fatalities to the public will be:

$$P = 27/6,600,000/(1980)-1950) = 1.4 \pm u \text{ E-7 deaths/Mg/year}$$

This value can be used as a basic figure for the probability of a large, "fatal" leak. It can be argued, with considerable justice, that this value does not apply to heavy water plant because of the safety measures taken and exclusion area around the plants. The calculations of atmospheric dispersion of H_2S indicate that danger to the public exists in cases when H_2S does not ignite. Knowing([33]) that H_2S inventory in 400 Mg of D_2O/year plant is about 600 Mg and by using the "analogy" method; we obtain for the Bruce HWP an over all risk H_1 equal to:

$$H_1 = 1.4 \text{ E-7} * 2400 * 600/400 = 5 \pm u \text{ E-4 deaths/year}$$

Other hazards due to heavy water plants will be estimated by using best data (population density (Table 24), weather conditions (Table 25), etc.) at our disposal which are from the Bruce area. Wind speeds and directions are being measured (Table 26) in the proximity of the Bruce heavy water plants (at the Goderich municipal airport) by Environment Canada([34]). The results will be extended to other heavy water plants in Canada. For the purpose of this study, we have assumed the annual output to be 2400 Mg of heavy water per year and this figure will be used to calculate the specific hazards.

The estimates hazards due to the differents scenarios will be developed more fully in the following sections, but at this stage, we will summarize the obtained results.

TABLE 27: Frequency distribution of Pasquill stability categories expressed in percent per month

	Year	Jan.	Feb.	March	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
A	3.7	0.6	2.8	4.3	4.4	5.0	7.0	7.3	6.0	4.6	1.4	0.6	0.3
B	8.8	3.2	5.5	9.0	10.3	11.6	13.9	13.4	12.4	13.4	6.7	4.3	1.9
C	11.6	9.3	9.5	11.4	13.2	13.6	13.6	13.1	13.4	12.1	12.0	10.7	7.9
D	60.6	79.5	69.5	59.7	57.2	50.8	42.3	41.1	45.5	54.2	67.3	77.1	82.3
E	6.9	3.9	5.7	6.5	6.3	8.0	9.3	11.8	9.6	7.3	6.7	3.7	4.2
F	8.4	3.5	6.8	9.1	8.5	11.0	13.9	13.2	13.2	8.5	5.8	3.6	3.5

From: Ontario Hydro - Bruce Heavy Water Plants A, B, D and Common Services Safety Report, September, 1979.

TABLE 28: Cumulative permanent population totals in the landward sectors

Radius	Sector				
	Northeast	East	Southeast	South	TOTAL
1.6 km	0	0	0	0	0
3.2 km	3	0	6	3	12
4.8 km	6	54	35	135	230
6.4 km	6	104	72	198	380
8.0 km	12	132	210	230	584
16.0 km	135	605	780	660	2,180
24.0 km	2,300	1230	1,490	4,050	9,070
32.0 km	4,380	2740	2,500	5,660	15,280
40.0 km	5,150	6620	4,000	7,000	22,770
48.0 km	6,300	9700	11,340	9,380	36,720
TOTAL	18,292	21,185	20,433	27,316	87,226

From: Ontario Hydro - Bruce Heavy Water Plants, A, B, D and Common Services Safety Report, September, 1979.

TABLE 29: Wind direction and speed classes measured at Goderich municipal airport

1979	Prevailing direction	Mean speed km/h	Speed classes (%) km/h					
			0	1-5	6-11	12-19	20-28	29-38
January	WW	263		3	21	19	31	22
February	S	16.8	2	6	28	26	26	11
March	S	17.0	1	6	29	28	24	10
April	NNW	16.9	3	7	31	29	20	6
May	S	14.5	3	7	28	37	22	3
June	SSW	14.8	6	8	28	27	26	5
July	NNW	8.9	17	12	41	20	10	
August	SSW	10.6	12	16	35	25	10	2
September	SSW	14.4	2	5	32	41	18	2
October	W	19.9	1	4	20	22	33	19
November	W	20.6	2	6	17	22	33	13
December	W	22.7	1	2	11	26	31	23
Annual								
Average (%)	—		4.5	6.8	26.8	26.8	23.7	10.5
Speed (m/s)	—		0	0.8	2.4	4.3	6.7	9.3

TABLE 30: Potential fatalities due to the operation of heavy water plants

Description of scenario	Hazard deaths/year/plant
Operating experience; 89% confidence level	< 4 E-2
Analogy method	5.0 ± u E-4
Continuous release of cold H_2S (10 kg/s)	8.2 ± 0.1 E-4
Continuous release of cold H_2S (100 kg/s)	1.6 ± 0.2 E-4
Continuous release of hot H_2S (100 kg/s)	4.0 ± 0.4 E-5
Instantaneous release, major catastrophy	6.1 ± u E-4
Transportation of H_2S, toxicity	1.1 ± 0.6 E-3
Transportation of H_2S increase in traffic	9.7 ± 1.0 E-4

Potential eye injuries due to use of H_2S are summarized in Table 31.

TABLE 31: Potential eye injuries due to the operation of heavy water plants

Description of scenario	Hazard Injuries/y/Plant
10 kg/s leak of hot H_2S	0.055 ± 0.005
100 kg/s leak of hot H_2S	0.013 ± 0.001
10 kg/s leak of cold H_2S	0.070 ± 0.010
100 kg/s leak of cold H_2S	0.018 ± 0.001
Transportation of H_2S, toxicity	0.260 ± 0.160
Transportation of H_2S, increase in traffic	0.000 ± 0.001
T O T A L	0.420 ± 0.160

Hazards calculated by the probabilistic approach for differents scenario cannot be simply added together because many of these events are interdependent. For this reason and for sake of conservation the highest value will be used in calculation of the over all risk of the type H_1. This type will be obtained by adding the highest hazard due to the occurrence of leaks plus hazards due to other independent causes such as earthquakes and plane cashes.

Now, we need to nnormalize the hazard figures obtained to production of electricity. We know[38] the average losses of heavy water in the Pickering power plant from 1975 to 1977:

Unit	#1	#2	#3	#4	Average
D_2O loss (kg/h)	1.267	1.034	0.937	1.022	1.065

Net electrical output of Pickering reactors is 515 MW and consequently in order to produce 1 GWy of electricity, the reactor will need 18 Mg of heavy water for the upkeep. Pickering reactors also use a large amounts of heavy water as moderator (301 Mg) and coolant (143 Mg). The useful life of the sation is about 30 years and consequently 28.7 Mg of heavy water per year and GWe are needed for inventory. For reactors having a capacity factors of 80%, overall amount of heavy water needed will be 53.8 Mg/y/GW.

Different types of hazards to the public, due to the heavy water production and normalized for 1 GWy of electricity, are summarized in Table 32.

TABLE 32: Hazards due to the heavy water production

Type of hazard	H_1	H_2	H_3	TOTAL
Fatalitics	3.1 ± u E-5	2.5 ± 1.3 E-5	2.2 ± 0.2 E-5	7.8 ± u E-5
Injuries	1.6 ± 0.2 E-3	5.8 ± 3.6 E-3	6.7 ± 2.2 E-5	7.4 ± 3.6 E-3

4.1 Ground Level Concentrations for Continuous Release of Cold Non-Burning Gas

Potentially, the most dangerous situation which can occur in a heavy water plant would be a large release of cold (32°C) non-burning H_2S. This case will be analyzed in the present section. Let's assume a discharge rate of 10 kg/s.

Using the program PLR, we can obtain the ground level concentrations at the distance of 1 km and we can calculate the surface area where H_2S would cause fatalities and injuries.

TABLE 33: Ground level concentrations of cold H_2S released at a discharge rate of 10 kg/s

Weather class	A	B	C	D	E	F
Wind speed (m/s)	1	2	3	5	2	1
Concentration at 1 km (g/m^3)	0.05	0.1	0.16	0.2	1.5	6
Lethal area (km^2)	0	0	0	0	0	0.2
Lethal radius (km)	0	0	0	0	0	3
Harmful area (km^2)	0	0.04	0.21	0.47	1.75	11.5
Harmful radius (km)	0	1.1	1.5	2.5	6.0	19

Note: Wind speeds have been selected using data from([34]). Harmful area is an area where the concentration of H_2S is greater than 0.1 g/m^3 and where eyes would suffer injuries.

Danger for the public for 10 kg/s discharge rate is considerable for F weather category. A greater discharge rate of H_2 would induce the proportionally greater danger and for 1000 kg/s rate, the danger would exist for all weather categories. A leak of 10 kg/s of H_2S may originate in many places in a heavy water plants. Some of the possible escape routes are the failure of rotating seals, a rupture of a small pipe in the cold section, a formation of a hole in large diameter pipes, in vessels or the storage tanks, etc. Probability of such events is very difficult to quantify and we have decided to use statistics on fires and explosions at refineries to estimate this probability.

A petroleum refinery is of the similar complexity as a heavy water plant and occurrence of a serious fire or explosion is usually a consequence of failures described previously. For this reason, we believe that operating experience of refineries can be applied to heavy water plants.

According to Bowen([9]), there are about 700 refineries in the western world and records of fires are kept by the American Petroleum Institute and by the Fire Research Station in the U.K.

From these records, we can calculate the probability of a fire causing a loss of more than 50,000 $ which is equal to 0.2/y.

Another problem encountered is to estimate the probability that the leak will go undectected and will not be ignited by crews or that H_2S detectors in the plant will "miss" the leak. We believe this to be an unlikely event and assigned to it a probability of 1 E-2. Thus, the over all probability of the leak will be 2 E-3 events/year.

The hazard for the public will be:

$$H_1 = P\ D \sum_{i=6}^{6} A_i W_i \qquad \ldots (4.1)$$

where P = the probability of the leak (2 E-3)

A_i = the area affected during weather conditions i (Table 3)

W_i = the probability of weather conditions of class i (Table 27)

D = the population density in affected area.

In our case, we obtain:

$$H_1 = 2\text{ E-3} * 25 * 0.084 * 0.2 = 8.4 \pm 0.1\text{ E-4 deaths/year}$$

Potential number of eye injuries can also be calculated using Equation (4.1). In this case, we obtain:

$$H_1(i) = 2\ E\text{-}3 * 25 * 1.4 = 0.07 \pm 0.01 \text{ injuries/year}$$

The same calculations were repeated assuming a larger leak (100 kg/s).

For fatalities, we will obtain:

$$H_1 = 2\ E\text{-}5 * 25 * 0.36 = 1.6 \pm 0.2\ E\text{-}4 \text{ deaths/year}$$

For eye injuries, we will have:

$$H_1(i) = 2\ E\text{-}5 * 25 * 35.9 = 1.8 \pm 0.1\ E\text{-}2 \text{ injuries/year}$$

TABLE 34: Ground level concentrations of cold H_2S released at a discharge rate of 100 kg/s

Weather class	A	B	C	D	E	F
Wind speed (m/s)	1	2	3	5	2	1
Concentration at 1 km (g/m^3)	0.53	0.01	1.76	4.8	14.7	66
Max concentration (g/m^3)	196	3620	4380	17900	32700	n.a.
Distance of C max (m)	3130	10	8	2	2	2
Lethal area (km^2)	0	0	0	0.09	0.48	2.9
Lethal radius (km)	571	709	934	1759	3672	7960
Harmful area (km^2)	0.63	1.8	2.5	9.1	37	325
Harmful radius (km)	2	3	4.3	12	29	100

Note: Q = 0 cal/s

4.2 Ground Level Concentrations for Continuous Release of Hot Non-Burning Gas

The ground level concentrations for hot non-burning gas discharge can be calculated using calssical Gaussian equation combined with the plume rise formula. The calculations begin with the determination of the plume rise due to the buoyancy of hot H_2S. Heat emission rates for 10 kg/s leak assuming T = 130°C are:

$$Q = 10^4 \ (130 - 25) \ 0.24 = 252{,}000 \text{ cal/s}$$

$$F = 9.81 * 10^4 * 105 / 1539 / 303 / 3.14 = 7 \ m^4 s^{-3}$$

Assuming the actual release height of 0 m, the ground level concentration of H_2S can be calculated using program PLR.

TABLE 35: Ground level concentrations of hot H_2S released at a discharge rate of 10 kg/s

Weather class	A	B	C	D	E	F
Wind speed (m/s)	1	2	3	5	2	1
Plume Rise (m)	35	18	12	7	45	25
Concentration at 1 km (g/m^3)	0.05	0.1	0.17	0.47	0.16	1.02
Max concentration (g/m^3)	1.06	1.92	3.27	15	0.2	1.08
Distance of C max (m)	208	143	115	468	1600	1300
Lethal area (km^2)	0	0	0	0	0	0
Lethal radius (m)	0	0	221	372	0	0
Harmful area (km^2)	0	0	0.20	0.47	0.74	9.3
Harmful radius (m)	766	998	1357	2078	4808	18936

Notes: Q = 252,000 cal/s
F = 7 $m^4 s^{-3}$

As can be seen from Table 35, a small leak of hot non-burning H_2S can cause eye injuries in certain weather conditions but is not lethal behind the exclusion area. The potential number of eye injuries can be calculated using the following equation:

$$H_1(i) = 2\ E\text{-}3 * 25 * 1.1 = 0.055 \pm 0.005 \text{ injuries/year}$$

Now let's repeat the same calculations assuming a larger leak of hot (130°C) non-burning H_2S released at ground level. The heat emission rate Q will be in this case 2,520,000 cal/s and buoyant force $F = 70\ m^4 s^{-3}$.

TABLE 36: Maximum ground level concentration of H_2S released at a discharge rate of 100 kg/s

Weather class	A	B	C	D	E	F
Wind speed (m/s)	1	2	3	5	2	1
Plume Rise (m)	181	91	61	36	99	66
Lethal area (km^2)	0	0	0	0.08	0	0
Lethal radius (km)	0	0	0	1.5	0	0
Harmful area (km^2)	0.61	1.65	2.3	8.9	21	.242
Harmful radius (km)	1.5	3.2	4.8	12	24	96
Concentration at 1 km (g/m^3)	0.44	1.7	1.1	2.4	~ 0	~ 0

Notes: Lethal and harmful area correspond to an area where the concentration of H_2S is greater than 2 and 0.1 g/m^3 respectively.

Potential number of eye injuries can be calculated using the following equation:

$$H_1(i) = 2\ E\text{-}5 * 25 * 27 = 0.013 \pm 0.01 \text{ injuries/year}$$

We have assumed that probability of occurrence of such a large release is 100 times smaller than for the leak of 10 kg/s. For potential fatalities, we will obtain:

$$H_1 = 2\ E\text{-}5 * 25 * 0.08 = 4.0 \pm 0.4\ E\text{-}5 \text{ deaths/year}$$

4.3 Ground Level Concentrations for Continuous Releases of the Burning Gas

A burning H_2S due to the buoyant forces will rise to the considerable height before dispersing. This is a very important factor which accounts for a relatively low ground level concentrations of H_2S. In order to assess the danger to the public, we will calculate the maximum ground level concentrations of SO_2 using Gaussian dispersion equation and plume rise formula developed earlier. The first case that will be considered is the consequences of a "small" (10 kg/s) leak of a burning H_2S. Heat of combustion of H_2S is 3632 calories/g and consequently, the heat emission rate Q will be 3.63 E+7 cal/s. The corresponding plume rises and the maximum ground level concentrations are shown in the following table.

TABLE 37: Maximum ground level concentrations of SO_2 due to the discharge of 10 kg/s of burning H_2S

Weather class	A	B	C	D	E	F
Wind speed (m/s)	2	4	6	8	4	2
ΔH, Brummage (m)				91	272	1650
C max (ppm)				1.5	0.05	~ 0
X max (m)				2612	47 km	—
ΔH, Briggs (m)	1484	742	494	371	229	288
C max (ppm)	1.6	0.8	0.8	0.5	9	0.1
X max (m)	2470	4391	7013	26 km	29 km	435 km

Notes: $F = 1368\ m^4 s^{-3}$
$Q = 3.6\ E+7$ cal/s
The lowest plume rise value was used in calculations.

As can be seen from the data above, the ground level concentration and the plume rise depend very strongly on weather conditions and can vary considerably.

It appears that a burning H_2S escaping at a rate of 10 kg/s does not present a danger to the public due to the high plume rise and an efficient dispersion in the atmosphere. Higher discharge rates of burning H_2S can occur in a heavy water plant but presently we do not have any formulas which can be used to calculate the plume rises for heat emission rates greater than 10^8 cal/s.

4.4 Ground Level Concentration for Instantaneous Release of Burning Gas

An instantaneous release of H_2S, followed by explosion can occur in a heavy water plant during a major catastrophy such as a strong earthquake or crash of a heavy aircraft. The cloud formed would rise owning to its buoyancy and original vertical momentum, being carried along by the wind in the horizontal direction. The plume rise from an instantaneous point source was treated by Morton et al.([37]). The total buoyant force F imparted to a large volume of entrained air is given by:

$$F = gQ/c/\rho/T \qquad \ldots (4.2)$$

and the plume rise ΔH for stable atmosphere is equal to:

$$\Delta H = 2.66\ (Q/\rho/c)^{0.25}\ (-G)^{-0.25} \qquad \ldots (4.3)$$

where Q = the instantaneous heat emission (cal)
G = the potential temperature gradient
c = the specific heat of the air (0.24 cal/g)
ρ = the density of the air (1293 g/m^3).

If we assume that the total inventory of H_2S (for example 1000 Mg) will burn in a few seconds, then we obtain:

Weather category	A	B	C	D	E	F
Temperature grad (°C/100 m)	-4	-1.8	-1.6	-1.0	-0.5	+1.5
Plume rise (m)	1873	2287	2355	2619	3150	3150*

* For F category we cannot use the plume rise formula but the maximum mixing height which varies with time and location. We use the same height as for category E.

The cloud of SO_2 (assuming 100% combustion) will disperse depending on the atmospheric conditions. The classifical Gaussian formula for the point source and instantaneous release can be applied in this case and using Slade's[5] diffusion coefficients, we will obtain the following expressions for exposure.

Class	Conditions	Formula	
A, B	Unstable	$\psi = 4.2\ QX^{-1.65} \exp(-1.78\ H^2\ X^{-1.46})$	... (4.4)
C, D	Neutral	$\psi = 35.5\ QX^{-1.62} \exp(-\ 22\ H^2\ X^{-1.40}\ )$	... (4.5)
E, F	Stable	$\psi = 330\ \ QX^{-1.50} \exp(-200\ H^2\ X^{-1.22}\ )$	... (4.6)

where Q = quantity of H_2S injected (g)
X = distance (m)

From these, the ground level exposure can be easily calculated.

TABLE 38: Maximum ground level exposure of SO_2 due to the instantaneous release and combustion of 1000 Mg of H_2S

Weather category	Unstable	Neutral	Stable
Annual frequency (%)	12.5	72.2	15.3
Plume rise (m)	2080*	2508	3150
Maximum exposure (gs/m)	4.3	n.a.	n.a.
Distance of max exposure (km)	48	n.a.	n.a.
Lethal radius (km)	0	0	0

* An average for two categories.

n.a.: Not applicable.

Note: For greater distances than 15 km, the formula must be used with caution, we have limited our calculations to 50 km distance.

From the data above, it can be seen that this type of release does not represent a hazard to the population. The scenario above assumes implicitely complete combustion of H_2S. This is improbable to happen and we have repeated our calculations assuming a 50% combustion. The results obtained are shown in the following table.

TABLE 39: Maximum ground level concentrations of SO_2 due to the instantaneous release and 50% combustion of 1000 Mg of H_2S

Weather category	Unstable	Neutral	Stable
Plume rise (m)	1645	2326	2760
Probability of occurence (%)	12.5	72.2	15.3
Wind speed (m/s)	2	3	2
Maximum exposure (gs/m)	3.6	n.a.	n.a.
Lethal radius (km)	24-50	n.a.	n.a.
Lethal area (km^2)	259	0	0

Release of 1000 Mg of H_2S could happen as a consequence of major catastrophy such as an earthquake of the magnitude 9 or a crash of a heavy airplane. We dont known the probability of occurrence of the earthquake but probability of a heavy airplane crash was estimated to be 1.5 E-6.

The lethal area was calculated using the program INRL and using for lethal exposure value of 3 gs/m^3. Using equation (4.1), the hazard for the population will be equal to:

$$H_1 = 0.5 * 1.5\ E\text{-}6 * 25 * 0.125 * 259$$
$$= 6.1 \pm u\ E\text{-}4\ \text{deaths/year}$$

The risk estimated was multiplied by 0.5 because in the Bruce area there is roughly 50% chance that wind will be blowing toward the lake Huron.

4.5 Hazards Due to the Transportation of Hydrogen Sulfide to Heavy Water Plants

Production of heavy water involves the transportation of large amounts of H_2S to the plants. This activity constitutes a potentially significant hazard to the public. To quantify this hazard, we will use the formula (1.29).

No transportation accidents (by trucks or rail-wagon) involving H_2S and causing a death to a member of the public by poisoning were reported up to 1980. But statistical data do exist for other hazardous chemicals. According to Statistics Canada([8]) a probability of derailment of a freight car resulting in a spill is 2.6 E-8 events/year/km. Hydrogen sulfide used at Bruce heavy water plant is supplied

by([38]) THIO-Pet Chemicals Ltd., Fort Saskatchewan, Sask and Montana Sulphur and Chemicals Co., Billings, Montana, which means that H_2S is transported over a distance of approximately 3000 km. From Ontario Hydro reports([39]), we can estimate the consumption of H_2S. For 1980 the Ontario Hydro reports the following quarterly releases of H_2S to the flare:

Quarter	II	III	IV	Average
Release (Mg)	517	208	350	358

To this we need to add H_2S released to the water (95 Mg per year) and will obtain the overall consumption of 1528 Mg of H_2S per year. Capacity of a railroad tankers used for H_2S is 43.6 Mg([39]) which means that 35 such carloads must be delivered. In order to estimate average consequences per accident, we will assume a discharge rate of the leak of 10 kg/s. Under these circumstances, the fatal ranges were previously by calculated and are shown in Table 33. Assuming an average population density of 25 persons/km^2, and frequency distribution listed in Table 27, the hazard due to the toxicity of H_2S will be:

$$H_2 = 2.6 \text{ E-8} * 3000 * 35 * 0.2 * 0.084 * 25$$
$$= 1.1 \pm 0.6 \text{ E-3 deaths/year}$$

The potential number of eye injuries can be assessed in the same way as the number of fatalities. Area where the concentration of H_2S exceeds 0.1 g/m^3 (threshold value for eye injuries) for different weather conditions are also shown in Table 33. Assuming population density of 25 persons per square km and the frequency listed in Table 27, we will obtain:

$$H_2(i) = 2.6\ E\text{-}8 * 3000 * 35 * 3.8 * 25$$
$$= 0.25 \pm 0.16 \text{ injuries/year}$$

The probabilities of a person being killed or injured by a train in accidents at highway crossings were calculated earlier and from these, the hazards H_3 and $H_3(i)$ can be estimated:

$$H_3 = 9.2\ E\text{-}9 * 3000 * 35 = 9.7 \pm 1.0\ E\text{-}4 \text{ deaths/year}$$

$$H_3(i) = 2.5\ E\text{-}8 * 3000 * 35 = 2.6 \pm 1.0\ E\text{-}3 \text{ injuries/year}$$

5. NUCLEAR POWER PLANTS

There are relatively few chemicals used at a nuclear power station. Among the most important, we can cite the chemicals used for water treatment (chlorine, hydrazine, morpholine, ion exchange resins), chemicals used for cleaning purposes, chemicals used in electric equipment (transformer oil, PCB, etc.), lubrification oil and others. There is only one chemical which in our opinion may present a hazard, namely chlorine. Chlorine is added periodically to the condenser cooling system to prevent the accumulation of biological growths on condenser tube surfaces. General practice is to add chlorine in sufficient quantity to provide a residual level of 0.5 ppm in the condenser discharge. A typical dosage schedule is for 20 minutes every six hours for each half of a condenser. Knowing that 600 MW CANDU reactor requires 32 m^3/s of water for cooling([35]), we can calculate the annual chlorine consumption which will be 56 Mg per 0.515 GWy/net.

Chlorine is usually delivered in 16 ton tank trucks([40]) and consequently, we will consider this quantity to be the basic amount of chlorine which can be released in a serious accident. In order to estimate the probability of such an event, we will use statistics on accidents and production of chlorine. According to Simmons([41]), there were 5 chlorine storage tank bursts with 120 tons of Cl_2 released and causing 106 deaths during a period from 1926 to 1974. From data published by Robertson([42]), we have estimated world wide chlorine production during this period which amounts to 4.2 E+8 Mg. Knowing the annual requirements of Cl_2 (56 Mg), we will obtain the probability of occurrence of a large leak of chlorine.

$$P = 5 * 56/420,000,000 = 7 \pm 1 \text{ E-7 events/year}$$

Now we must estimate the consequences of such a leak. We will consider two scenario; a burst of a storage tank resulting in an instantaneous release of total inventory of tank and a pipe rupture with a release rate of 10 kg/s. Exposure to chlorine is lethal when its concentration in the air is greater than 1000 ppm (2.5 g/m^3) during 30 mi[illegible]e.(^{40}) or more. Consequently the lethal exposure is 4500 gs/m^3 We will assume the atmospheric conditions for bruce nuclear power plant (Table 40).

The hazard to the public will be equal to:

$$H_1 = 7\ E\text{-}7 * 0.153 * 0.42 * 25 = 1.1 \pm 0.2\ E\text{-}6 \text{ deaths/year}$$

$$H_1(i) = 7\ E\text{-}7 * (0.12 * 0.125 + 0.54 * 0.722 + 14.5 * 0.153) * 25 = 4.6 \pm 0.7\ E\text{-}5 \text{ injuries/year}$$

The second scenario considered is the pipe rupture with a release rate of 10 kg/s. Such an event could occur for example as a consequence of an earthquake of magnitude 7 which probability was estimated to be 8 E-6 events/year. Other causes may be envisioned (corrosion, falling objects, etc.) but it is difficult to estimate their probabilities and for the purpose of this study we will assume the over all probability to be equal to 8 E-6. Consequences of the second scenario are listed in Table 41.

To calculate the hazard to the public, we can apply the formula used for the first scenario and we will obtain:

$$H_1 = 8\ E\text{-}6 * 0.084 * 0.12 * 25 = 2 \pm u\ E\text{-}6 \text{ deaths/year}$$

$$H_1(i) = 8\ E\text{-}6 * 1.39 * 25 = 2.8 \pm w\ E\text{-}4 \text{ injuries/year}$$

Finally, we will estimate hazard to the public due to transportation of chlorine. We assume first of all, that chlorine is delivered to the plant in 16 ton tank trucks from the nearest supplier. According to Ministry of Industry, Trade and Commerce, publication([24]), in provinces where nuclear power plants are located, are the following producers of chlorine:

Company	Plants	Distance to NPP (km)
Canadian Industries Ltd.	Bécancour, Qué.	40
	Cornwall, Ont.	280
	Dalhousie, N.B.	450
Dow Chemical of Canada Ltd.	Sarnia, Ont.	192
Stanchem	Beauharnois, Qué.	180

In our calculations, we will use the average trucking distance of 228 km.

TABLE 40: Consequences of instantaneous release of 10 Mg of chlorine at ground level

Weather category	Unstable	Neutral	Stable
Annual frequency (%)	12.5	72.2	15.3
Wind speed (m/s)	2	3	2
Exposure at 1 km (gs/m^3)	353	1863	78266
Lethal area (km^2)	0.00	0.00	0.42
Harmful area (km^2)	0.12	0.54	14.5

Notes: Lethal exposure = 4500 gs/m^3
Harmful exposure = 280 gs/m^3

TABLE 41: Consequences of a continuous release of chlorine at a rate of 10 kg/s

Weather class	A	B	C	D	E	F
Annual frequency (%)	3.7	8.8	11.6	60.6	6.9	8.4
Wind speed (m/s)	1	2	3	5	2	1
Concentration at 1 km (g/m^3)	0.05	0.1	0.18	0.48	1.47	6.6
Lethal area (km^2)	0	0	0	0	0	0.12
Harmful area (km^2)	0	0.04	0.21	0.47	1.75	11.5

According to Kalelkar, Partridge and Brooks([14]), the expected deaths per accident in urban and rural environments are 380 and 15 respectively. The relative urban and rural exposures are 0.1 and 0.9; therefore, we can expect the following consequences:

$$C = 0.1 * 380 + 0.9 * 15 = 51.5 \text{ deaths}$$

Combining the numbers, we will obtain:

$$H_2 = 1.6 \text{ E-8} * 4 * 228 * 51.5 = 7.5 \pm 7.5 \text{ E-4 deaths/year}$$

Number of injuries will be calculated by assumming that there are 33 injuries per death([50]) consequently:

$$H_2(i) = 7.5 \text{ E-4} * 33 = 2.5 \pm 2.5 \text{ E-2}$$

Consequently for the specific hazard, we obtain:

$$H_2^1 = 7.5 \text{ E-4}/0.5156 \text{ GWe}$$
$$= 1.5 \pm 1.5 \text{ E-3 deaths/GWy of electricity}$$

$H_2'(i)$ = 2.5 E-2/0.5156 GWe

= 4.8 ± 4.8 E-2 injuries/GWy of electricity

And hazard due to the increase in traffic will be:

H_3 = 4.9 E-9 * 4 * 228 = 4.5 ± 4.5 E-6 deaths/year

$H_3(i)$ = 1.8 E-7 * 4 * 228 = 1.6 ± 1.6 E-4 injuries/year

Different types of hazard due to the nuclear power plants and normalized for 1 GWy of electricity are summarized in Table 42.

TABLE 42: Hazards due to the nuclear power plants

Type of hazard	H_1	H_2	H_3	TOTAL*
Fatalities	6.0 ± u E-6	1.5 ± 1.5 E-3	8.7 ± 8.7 E-6	1.5 ± 1.5 E-3
Injuries	6.3 ± u E-4	4.8 ± 4.8 E-2	3.1 ± 3.1 E-4	4.8 ± 4.8 E-4

* Assuming a capacity factor of 80% for H_1.

6. WASTE DISPOSAL SITES

Disposal methods for nuclear waste depend on their activity. Low and medium level solid waste is usually buried and does not undergo any chemical processing and consequently does not present any "chemical" hazard to the public. Low level liquid and gaseous waste is dispersed into hydrosphere and atmosphere with minimal treatment and the same conclusion apply to this type of radioactive waste. Medium level liquid waste is chemically and physically treated but chemicals used (sodium carbonate and sulfate, ion exchange beds, filters, alun, etc.) being solids do not present hazard either. Medium level gaseous waste may be treated in many ways (low temperature adsorption on active carbon, absorption in fluorocarbons, washing with NaOH, etc.) but the procedures used also present very little chemical hazard for the public. Methods for the treatment of high level waste are yet to be selected. Many techniques have been used on a laboratory scale. Two basic approaches can be applied: encapsulation of spent fuel or fuel reprocessing and waste solidification; among matrices proposed for spent fuel encapsulation two are most frequently cited: glass and lead; neither of them presents an acute chemical hazard. Numerous techniques have been studied for fuel reprocessing. The most important one, PUREX method, uses the following chemicals: mineral acids for dissolution, kerosene a tributyl phosphate for extraction, sodium nitrite for reduction, and some others but none of these presents a chemical hazard. Taking into account an exclusion zone which would surround any future reprocessing plant, it is hard to envision any scenario by which public could be endangered by the chemical procedures used. Consequently, we conclude that chemical hazards due to waste processing of the type H_1 are negligible.

The same reasoning applies to hazards of the type H_2. Due to the low-toxicity nature of chemicals to be used in future reprocessing plants, the hazards due to the poisoning of the public during the transportation of chemicals are deemed to be negligible.

But there is one type of hazard which remains present, namely the type H_3 which estimates the probability of fatalities or injuries due to the increase of the traffic.

In order to estimate this risk we must study separately the two scenarios described previously, what is done in two following sections. We dont know what type of nuclear fuel disposal will be finally selected by the government and for this reason we are using higher figures in the final comparison of risks.

TABLE 43: Hazards due to the waste disposal

Type of hazard	H_1	H_2	H_3	$H_3(i)$
Reprocessing	0	0	1.5 ± 1.5 E-4	5.4 ± 5.4 E-3
Immobilization	0	0	4.2 ± 4.2 E-5	1.5 ± 1.5 E-3

6.1 Transportation Hazard Due to the Reprocessing of High Level Waste

The PUREX process([44]) is the most important reprocessing technology presently available, which is susceptible to be used in any future canadian reprocessing plant. This process consists in selective extraction of uranium and plutonium with tri-butyl-phosphate in kerosene. Considerable operating experience does exist for this process

and data on the amounts of materials entering and leaving the plant are available. North has published some values([45]) on the amount the waste generated at Nuclear Fuel Services Inc. plant which was built at the West Valley (N.Y.) and which operated for six years. This plant has produced 3000 m^3 of the waste for each 750 Mg of spent fuel. Assuming that all this waste originates mostly from materials used up during processing and assuming the average density of materials to be 1 g/cm^3, we would need 4 g of these in order to reprocess 1 g of spent fuel. The materials used are of varied nature (kerosene, TBP, acids, resins, HEPA filters, process equipment, etc.) and would be shipped from different places over different distances. Let's assume for the purpose of this study the average shipping distance of 500 km, truck as shipping medium and 10 Mg average shipping charge.

According to Critoph([26]) 133 Mg of uranium are needed to produce 1 GWy of electricity. This is equivalent to 151 Mg of UO_2 and it would result in practically the same amount of the spent fuel. Consequently 604 Mg of materials would be needed to reprocess this fuel and the hazards H_3 would be equal to:

$$H_3 = 604/10 * 500 * 4.9\ E\text{-}9 = 1.5 \pm 1.5\ E\text{-}4 \text{ deaths}$$

$$H_3(i) = 604/10 * 500 * 1.8\ E\text{-}7 = 5.4 \pm 5.4\ E\text{-}3 \text{ injuries}$$

6.2 Transportation Hazard Due to the Immobilization of the Spent Fuel

In Canada, no decision has been taken on the reprocessing of the spent fuel and recovery of plutonium. The government has stated ([46]) that no decision on fuel recycle will be taken until the conclusions of the International Nuclear Fuel Cycle Evaluation([47]) have been reviewed in detail. Consequently a technology is being developed for

the immobilization of spent fuel. Despite the fact that the development of technology is not yet completed its main features are clearly visible. The spent fuel will be imbedded in a metallic matrix (zinc or lead) and enclosed in a high-integrity containers with life of 300 to 500 years([48]).

Let's estimate the quantity of materials needed for immobilization. Canadian 37-element fuel bundle is 49.5 cm long, its outside diameter is 10.2 cm and the nominal coolant flow area (based on cold dimensions) is 34.21 cm^2. Consequently the void volume is equal to 1693 cm^3.

Arrangement of fuel elements in containers has yet to be specified, but assuming the closest packing possible it can be easily deduced from geometrical considerations, that additionnal 207 cm^3 would be needed for inter-bundle voids. Altogether, it can be assumed that the matrix would occupy at least 1900 cm^3 compared to the net fuel bundle volume which is equal to 2461 cm^3. A fuel bundle weights 23.6 kg of which 18.80 kg is due to uranium oxide.

Knowing that 151 Mg of UO_2 are needed to produce 1 GWy of electricity, it can be calculated that at least 15,260,638 cm^3 of lead or zinc would be required to immobilize the spent fuel. Let's assume that lead will be selected for the matrix, that the average shipping distance will be 500 km, that average shipping charge will be 10 Mg and the shipping will be done by trucks. In these circumstances the hazard H_3 will be equal to:

$$H_3 = 15,260,638 * 11.34 / 1\ E+7 * 500 * 4.9\ E-9$$
$$= 4.2 \pm 4.2\ E-5 \text{ fatalities}$$

and
$$H_3(i) = 15,260,638 * 11.34 / 1\ E+7 * 500 * 1.8\ E-7$$
$$= 1.5 \pm 1.5\ E-3 \text{ injuries}$$

7. REVIEW OF NON-RADIOLOGICAL

In this chapter, we will summarize results obtained earlier. Before doing so, we would like to emphasize some difficulties encountered during our study and which have a direct bearing on these results. First of all, we have faced a lack of experimental data on physiological effects of sublethal concentrations of hydrogen sulfide, hydrogen fluoride and ammonia on man. It is quite possible that a long-term low-concentration exposures to these chemicals may cause not yet documented illnesses or injuries. Data on the atmospheric behaviour and possible chemical interactions with aerosols of these gases are also limited. We were obliged to use in some cases rather simple models which can be, if sufficient time is available, further refined and improved. This is quite understandable when considering that risk assessment is a new field of study, which methodology is still being developed. Some models used could also benefit in a large degree from an experimental verification. Finally, in many cases, we were forced to use data based on a foreign experience which may not be completely relevant for canadian conditions. For all these reasons, the results obtained indicate an order of the magnitude rather than an exact values of hazard and should be viewed as such. The results obtained are subject to a large degree of uncertainty and much more time and work would be needed to improve precision. The results summarized in Table 44 should be examined with all this in mind.

TABLE 44: Non-radiological hazards due to the nuclear fuel cycle for 1 GWy of electricity produced

Phase of fuel cycle	Fatalities	Injuries
Mining	9.1 ± 7.2 E-4	3.3 ± 0.3 E-2
Refining	2.1 ± 0.3 E-5	2.9 ± 1.0 E-4
Heavy water production	7.8 ± u E-5	7.4 ± 3.6 E-3
Nuclear power plant	4.8 ± 4.8 E-3	1.5 ± 1.5 E-3
Waste treatment	1.5 ± 1.5 E-4	5.4 ± 5.4 E-3
Total hazard	6.0 ± 4.8 E-3	4.8 ± 0.7 E-2

8. RECOMMENDATIONS

During our study we have encountered many difficulties which are reflected in the following recommendations concerning the possible future work which needs to be done in order to increase the accuracy and precision of results:

1) Establishment of a good theoretical plume rise formulas for unstable weather classes.

2) Establishment of detailed data on the flight patterns around each nuclear facility. Such data should contain average annual frequencies of flights of different types of airplanes and their closest approach.

3) Development of a model for estimating the precision of results obtained for the poisoned area when there is a plume rise.

4) Establishment of the precision of the probability of failure of pressure vessels.

5) Determination of the precision of results obtained for the seismic risk and the increase of the accuracy of the probability of an earthquake of given magnitude.

6) Establishment of data describing the frequencies and magnitudes of leaks in heavy water plant.

7) To obtain some data on the probability of a human error in industrial environment.

8) Establishment of statistical data on accidents involving hydrogen fluoride.

9) Establishment of the impact of earthquakes of different magnitudes on a heavy water plant.

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